Bioenergy for Sustainable Development and Global Competitiveness: The case of Sugar Cane in Southern Africa

A compilation of Results from the Thematic Research Network: Cane Resources Network for Southern Africa (CARENSA)

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Thematic Report 2: Industry

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www.carensa.net

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This report was the result of several years of fruitful collaboration among the thirteen CARENSA partners along with subcontractors and others who contributed valuable ideas and detailed data. Many persons gave their time above and beyond what was called for in order to evaluate the role that sugar cane and other productive energy crops can play in supporting sustainable development and global competitiveness in southern Africa.

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ACRONYMS

BIG-CC  Biomass Integrated Gasifier - Combined Cycle
BIG/GT  Biomass Integrated Gasifier/ Gas Turbine
BIG/STIG Biomass Integrated Gasifier/Steam Injected Gas Turbine
BOD    Biological Oxygen Demand
CEST   Condensing Extraction Steam Turbine
CMC    Carboxy methyl cellulose
COD    Chemical Oxygen Demand
CTC    Copersucar Technology Center
DM     Dry Matter
DMC    Direct Microbial Conversion
DME    Department of Minerals and Energy
DSCT   Dehydrated Sugar Cane Tops
EBPT   Extraction cum Back Pressure Turbine
ECS    Environmental Consulting Services
ECT    Extraction and Condensing Turbine
EGSB   Expanded Granular Sludge Bed
ESP    Electro-Static Precipitator
FAO    Food and Agriculture Organisation of the United Nations
FFV    Flexible Fuel Vehicles
FT     Fischer Tropsch
GHG    Greenhouse Gas
GT     Gas Turbine
GTCC   Gas Turbine/Steam Turbine Combined Cycle
GTL    Gas to Liquid
HTM    High Test Molasses
IC     Internal Circulation
ICIDCA The Cuban Research Institute for Sugar Cane Derivatives
IE     Industrial Efficiency
IHTM   Integral high-test molasses
IPP    Independent Power Producers
INT    Brazil's National Technological Institute
LHV    Lower Heating Value
LTFF   Long-Tube, Falling-Film Evaporators
MEG    Monoethyleneglycol
MSIRI  Mauritius Sugar Industry Research Institute
PROALCOOL The official name for the Brazilian alcohol program that began in the 1970s
SADC   Southern African Development Community
SASOL  South African state company for coal-to-liquids, chemicals, and fuels
SASTA  South African Sugar Technology Association
SHF    Separate Hydrolysis and Fermentation
SRI    Sugar Research Institute
SSF    Simultaneously Saccharification & Fermentation
STAI   Sugar Technologists Association of India Sugar Industry
STIG   Steam-injected Gas Turbine Cycle
T&D  Transmission and Distribution
TNPL  The Tamil Nadu Newsprint and Papers Ltd.
TRS  Total Recoverable Sugar
TRS  Total Reducing Sugars
UASB  Upward Anaerobic Sludge Blanket
USAID  United States Agency for International Development
WEC  World Energy Council

UNITS AND SYMBOL

°GL  degree Gay-Lussac
%w.w.  Percentage weight by weight
Bl  Billion gallons
Bbl  Barrel of oil
GJ  Gigajoule
GWh  Gigawatt hour
H₂S  Hydrogen Sulphide
kJ/kg  kiloJoules per kilogram
kV  Kilovolt
kWh  kiloWatt-hour
mg/l  milligrams per litre
MJ/Nm³  Megajoules per nano cubic metres
Mt  Million tones
MW  Megawatt
MWe  Megawatt electrical
MWₜ  Megawatt thermal
N  Nitrogen
TC  Tonnes of cane
TCH  Tonnes of cane per hour
TWh  Terawatt-hour
Vvm  Unit volume of gas per unit volume of liquid per meter
This report covers the industry phase within the CARENSA work programme. The CARENSA series of reports provide a critical assessment on the role of sugar cane resources in promoting sustainable development and global competitiveness in Southern Africa. Among the many agricultural sources of biomass, sugar cane has special significance for the developing world, due to its high photosynthetic efficiency, its limitation to tropical and sub-tropical climates, and the long experience with its cultivation in developing countries. The CARENSA reports also briefly consider—with within a similar context—the role of other highly productive energy crops such as Sweet Sorghum. The CARENSA series includes the following reports:

- Thematic Report 1: Agriculture
- Thematic Report 2: Industry
- Thematic Report 3: Markets
- Thematic Report 4: Impacts
- Thematic Report 5: International Experiences and Comparisons
- Thematic Report 6: Synthesis and Integration

Growing concerns worldwide about the impacts of climate change and the world’s increasing dependence on fossil fuels have intensified interest in bioenergy and biofuels. The potential expansion of sugar cane and other highly productive energy crops in the developing world highlights important linkages among energy, environment and development goals across all scales—from local to global. As global markets develop and expand, it remains important that such crops be grown in the regions where they are most productive, so as to maximise their benefits and minimise negative impacts. The CARENSA reports address key issues across all relevant scales—local, national, regional, and global—based on the recognition that sugar cane has become a truly global resource for renewable energy and sustainable development. The reports draw on the many topics (work packages) within the CARENSA work programme, including:

- Agronomy & Land Resources
- Harvesting and Delivery
- Process Systems Analysis
- Fibre Resources
- Sugar Resources
- Policies and Regulations
- Trade, Financing, & Investment
- Implementation and Strategies
- Socio-economic Impacts
- Environmental Impacts
- Risk Analysis & Competitiveness
- Sustainable Development
- International Experiences & Comparisons
- Industry Perspectives
- Communications
- Dissemination

CARENSA brought together many different types of actors and stakeholders, representing government agencies, NGOs, industry, research institutes, university research groups, and international organisations:
In addition to the network members, representatives from several other organisations from both the public and private sectors were invited to CARENSA workshops and seminars.

Sugar cane has come to be associated with the production of bio-ethanol, particularly in Brazil, where bio-ethanol meets a significant share of the demand for transportation fuels. Sugar cane has also been associated with cogeneration of electricity from the significant amount of residues that remain after production of sugar, such as in Mauritius, where a significant share of the country’s electricity generation now comes from the efficient systems installed at sugar factories. Many other countries have been encouraged by developments in Brazil, Mauritius, and elsewhere, and have established new programmes for expanded energy generation from sugar cane. Indeed, some future scenarios are based on using sugar cane predominantly or even solely for its energy production, as it provides an economically competitive and climate neutral renewable energy resource.

Although the CARENSA reports focus on bio-ethanol and cogeneration because of their commercial significance, the reports also include some of the other “by-products” or “co-products” that can and have been produced from the sugar cane crop. Sugar cane is in fact also significant for its versatility as an economic resource; a wide variety of products have been developed from it to provide food, feed, and fibre as well as fuel. This versatility of sugar cane is valuable in economic terms, as it allows companies and investors to reduce the risk associated with relying mainly—or only—on one product, such as has been the case with sugar markets, where rather complicated preferences and special arrangements have been used to protect certain segments of the market from competition. As these preferential markets are gradually removed, the discipline of market competition can help to unleash the potential of sugar cane as a global and sustainable resource.
This study is a collaborative effort on renewable energy in the sugar cane industry under the work programme of the Cane Resources Network for Southern Africa (CARENSA). This report evaluates the techno-economic status of sugar cane processing, bagasse energy production, steam economies in sugar factories, bagasse cogeneration potential, ethanol production options and distillery configurations, and prospects for various sugar and fibre co-products. The report also outlines and compares alternative strategies for co-production of sugar, ethanol and electricity.

The process of raw sugar manufacture from sugar cane is fairly standardised in Brazil, Asia and in the southern African Development Community (SADC), consisting of similar unit operations: cane preparation, milling or diffusion, clarification, evaporation, crystallization and steam/electricity production. Condensing Extraction Steam Turbine (CEST) technologies are the state-of-the-art technology for bagasse cogeneration in terms of mature, fully commercialised options. CEST systems for bagasse cogeneration have been used extensively in Mauritius, Reunion and India.

In Mauritius, bagasse cogeneration systems using high pressure (up to 82 bar) and high temperature (up to 525°C) produce 75–140 kWh surplus electricity per tonne of cane processed (kWh/tc), compared to 0-15 kWh/tc in typical SADC factories outside of Mauritius. In India, 67 bar pressure and 495°C temperature configurations have been established in recent years, while most Brazilian sugar mills have been upgraded to an average of 40 bars. The potential for bagasse cogeneration in SADC factories is estimated as ranging from 1091 GWh (at 20 bar and 325°C) to 5675 GWh (at 82 bar and 525°C). The experiences in Mauritius and India could thus be replicated in many SADC countries to expand sustainable energy production from domestic biomass resources.

The reference case for ethanol from sugar cane is based on the experience in Brazil, where an extensive and highly competitive ethanol programme has been developed. Methods for processing cane juice can differ. Multistage juice treatment furnishes the best results on fermentation parameters but requires increased steam consumption and higher relative investment cost. The Melle-Boinot process is the most popular fermentation process, with alcohol productivity comparable to continuous fermentation, typically 4–7 kg ethanol per unit volume of fermentation tank (m³) per hour. The preferred configuration is the annexed distillery in which various combinations of sugar and ethanol can be produced.

Although ethanol and cogenerated electricity are currently the most economically significant products from sugar cane, there are also a wide variety of other co-products whose commercial value and market share is likely to grow. Examples of fibre-based products include particleboard, corrugated boxes, and furfural. The sucrose stream of the cane also offers a wide range of co-product options, such as various organic acids, monosodium glutamate, xanthan, dextran gums, and bioplastics. Through international investment and regional cooperation, the diversity and flexibility of sugar cane as a renewable resource can be employed as a powerful tool in support of sustainable industrial development, economic growth, and poverty reduction in southern Africa.
1. Introduction

The sugar cane plant is one of the world’s most cost-effective and diversified renewable resources, offering many alternatives for production of food, feed, fibre, and energy. Owing to climatic factors, sugar cane is found predominantly in the developing world and as such represents a valuable tool in the simultaneous search for sustainable energy sources and new development alternatives. Sugar cane resources support a variety of uses and products in the energy, industrial, and agricultural sectors, based on different product streams: sugar, molasses/juice, and crop residues, as shown in Figure 1.

Figure 1: Schematic diagram of sugar cane processing streams and products

Refined or brown sugar, cogenerated electricity and ethanol are currently the most important cane co-products in commercial terms, and have therefore been a major focus in this report, but there are many other potential industrial and agricultural products. These products are generally referred to as *co-products*—rather than by-products—of the sugar cane agro-industry, since they actually result from processes that are simultaneous and/or not easily divisible. Sectors such as pharmaceuticals and various chemical industries have relied on sugar cane co-products as building blocks for other commercial products. The various protein and carbohydrate constituents of co-products such as molasses are used for animal feeds and other agricultural products.

1.1. Thematic Focus

An industrial analysis of sugar cane begins with the delivery of sugar cane stalks to the sugar factory, where a fairly complicated set of processes ultimately extract sucrose from the sugar cane stalks. The industrial side of the sugar cane agro-industry is assumed here to also include a boiler house, where steam and/or electricity are produced. It may also include other facilities, depending on what other products are to be made, among the various options referred to in Figure 1.
In energy terms, it is useful to distinguish between two major ‘resource streams’, one associated with the cane juice that includes the various sugars; the other that includes the fibre contained. The sugar resource stream includes the various types of sugars that can be fermented into ethanol, while the fibre resource stream can include bagasse remaining at the factory, as well as residues left in the fields. The technical conversion facilities can then be divided into three categories:
- ethanol distillery – operates on the ‘sugar’ resource stream.
- cogeneration plant – relies on the ‘fibre’ resource stream.
- other facilities, e.g. for downstream products from one or both resource streams.

The report focuses especially on the sugar and fibre resource streams from the sugar cane plant and the processes and technologies that separate and exploit these resources. The body of the report is divided into five main sections:
1. Process systems analysis at a cane sugar factory.
2. Fibre resources, particularly with respect to bagasse utilisation.
3. Sugar resources and fermentation of sugars into ethanol.
4. Other fibre co-products from field residues and bagasse.
5. Co-product strategies, especially for sugar, ethanol, and cogenerated electricity.

The focus is on factory configurations that are common in SADC countries or those configurations that could potentially be accomplished with retrofits. Benchmarks are based on accepted performance metrics for sugar, ethanol, and cogeneration. Various other downstream products are discussed but are not assessed in detail.

1.2. Objectives

The main objectives of this report are as follows:
i) To compare performance characteristics of typical sugar factories in southern Africa with state-of-the-art factories, with special attention to steam economy and energy efficiency;
ii) To identify key issues and choices with respect to juice-fibre separation, with emphasis on bagasse cogeneration and ethanol production options;
iii) To develop performance benchmarks for optimal cost-effective cogeneration and distillery configurations; and
iv) To identify alternative co-products utilisation options for both the fibre and sugar resource streams.

1.3. Approach

The work programme included the following elements:
- Research on available information and reports;
- Meetings and consultations with key government and private sector stakeholders;
- Preparation of working reports on sugar cane resources from different countries;
- Organisation of workshops/meetings where key findings and preliminary strategies were discussed; and
- A series of focus group sessions for exploring particular issues.

Feedback from the above meetings and sessions was then used to update the preliminary findings, and formed a valuable input to the current document. Subsequently, an international workshop was held where key stakeholders of the
sugar industry and other relevant stakeholders were invited. The aim of the workshop was to raise awareness on key global issues and international experiences and to share the industry perspectives in particular to market development. The information shared at the workshop event proved to be very useful and was used in the preparation of this report.

1.4. Key Outputs

The key outputs of the report are as follows:
- Analysis of the status and techniques of sugar production in different world regions.
- Synthesis of alternative bagasse cogeneration technologies and the energy production potential for different systems and in different countries in Southern Africa.
- Evaluation of ethanol production options and distillery configurations.
- Other co-product development opportunities from sugar cane resources.
- A set of benchmarks for bagasse energy cogeneration and ethanol production.

1.5. Structure of the Report

The thematic report 2 on industry is structured to include the following:
- Section 2 reviews sugar factory processes and systems, and compares performance characteristics, with special attention to steam economy and energy efficiency.
- Section 3 evaluates fibre resources, with emphasis on cogeneration options.
- Section 4 addresses sugar resources, emphasising ethanol production, but including a brief review on other uses of the sugar resource stream and associated products.
- Section 5 reviews other fibre co-products that can be obtained from sugar cane.
- Section 6 considers alternative co-production strategies in the sugar industry.
- Section 7 summarises the findings of the study.
2. Process Systems Analysis – Sugar Industry

Sugar production in the mill is perhaps best characterised not as a manufacturing process but as a series of liquid-solid separations to isolate the sucrose (Blume, 1985). The process of extracting sucrose from sugar cane includes a number of operations that extract the juice, while the fibrous residue, known as bagasse, is a by-product. Conveyor belts carry the bagasse to boilers for generation of steam and electricity for the process. This section describes the various processes in detail, focusing on conditions that are typical in sugar factories in SADC countries.

2.1. Review of Sugar Manufacturing Process and Operations in SADC Countries

A schematic diagram of a typical raw sugar manufacturing plant in SADC countries is as shown in Figure 2.

![Schematic diagram of a raw sugar manufacturing plant](source)

Figure 2: Schematic diagram of a raw sugar manufacturing plant

Source: Seebaluck (2004)

The process of raw sugar recovery consists of two distinct departments, namely, the milling department and the boiling house.
2.1.1. Milling

The milling department comprises of two major workstations, which are cane preparation and juice extraction.

Prior to milling, the cane is unloaded, placed in large piles and sometimes cleaned\(^1\) before being conveyed for cane preparation. Cane preparation consists of breaking the hard structure of the cane and is usually done by a combination of knives, which act as levellers, and shredders. Its aim is to present to the milling unit an evenly prepared mat of cane with a high level of opened cells, at a relatively constant rate. A rotor with swinging hammers and a shredding plate forms the shredder.

For juice extraction or crushing of the prepared cane, multiple sets of three-roller mills are commonly used, although in some countries some mills consist of four, five, or six rollers in multiple sets. Two-roller milling units have been the emerging technique, practiced in Australia and India, and more recently in Mauritius.

When the cane undergoes the process of preparation and crushing, most of the juice cells are broken. The milling process squeezes the prepared cane as it passes between two rotating rolls under high pressure such that, most of the juice of the ruptured cells is drained out and only a part remains adhered to the surface of the fibre due to surface tension. Hence, bagasse carries some juice in the fibre cells and also juice is retained on the surface fibre. Sugar present in both of these parts of juice in bagasse is reduced further in the following mills. Ultimately whatever sugar is carried after the last mill is lost in final bagasse.

Diluting the residual juice by imbibition water, reduces sugar retained on the surface of the bagasse. This process has no effect on the unbroken juice cells, unless the imbibition liquid is hot enough that the cells are broken. There are various methods of addition of water in the imbibition process. However, the most popular method adopted is compound imbibition which is based on counter-current extraction, and this is used in most SADC sugar factories. It involves the application of water (or juice from the penultimate mill) on bagasse in the last mill. The juice extracted by the last mill is then fed to the bagasse going to the preceding mill and so on until it reaches the second mill of the milling tandem. In this way, the extracted juice flows-counterflow with the cane being milled and the extraction efficiency in a properly designed, maintained and operated mill can reach values up to 98%.

Thus, the juice extracted by dry crushing from the first mill, together with that from the second mill of a milling tandem, form the mixed juice stream. This juice is processed for sugar recovery.

Typical milling tandems in Mauritian sugar factories consist of four to seven three-roller mills, each mill generally driven by individual drives (electrical or high pressure steam). Nearly half of the sugar factories have four three-roller milling tandems and the other half have five three-roller milling tandems; with the exceptions of one sugar factory possessing a six three-roller milling tandem, and another one having a seven

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\(^1\) Cleaning by washing is common in South America. Dry cleaning by dropping chopped cane through a wind current (i.e. similar to chopper harvester leaf separation) is under development at a few factories in South America, Australia and Mauritius.
three-roller milling tandem. Almost all of the milling units are equipped with Donnelly chutes and high diameter feed rollers. Use of pressure feeders and underfeed rollers is not popular in Mauritian sugar factories, but is common in South African factories. At the current milling rates, milling performance is very high in terms of extraction compared to those in the sugar industries in other parts of the world. The average cane preparation index\(^2\) is 88, and an average mill extraction of 97.2% is obtained throughout the island. India has an average mill extraction of 96.0%. In Brazil, the milling tandem is formed by four to seven mills, and the extraction efficiency in a properly designed, maintained and operated mill can reach up to 97.5%.

Mills in Mauritian sugar factories are mostly driven by back-pressure steam turbines or electrical motors except for one sugar factory where its mills are hydraulically driven. The hydraulic system consists of a hydraulic motor fed with oil that is pumped by a fixed-speed AC motor, and the hydraulic motor is mechanically coupled to the drive shaft of the mill. A recent trend in the sugar plants is to replace steam turbines by electric motors where the speed of the rollers is controlled by the use of inverters. Since all the mills cogenerate electricity for sale to the public grid, upgrading to electric motors is generally a cost-effective investment\(^3\).

2.1.2. **Diffusion**

An alternative method for juice extraction from sugar cane is by diffusion, which is quite common in South African sugar factories. Though the technology is not in use in Mauritius, a diffuser station is currently being proposed for one sugar factory in the southern part of the island. Diffusers constitute about 80% of all installed capacity in southern Africa, including Swaziland and Zimbabwe. However, installation of diffusers in other cane producing areas of the world is much lower.

![Figure 3: Juice extraction by diffusion](image_url)

Diffusion is a combination of leaching (lixiviation or washing) and dialysis (diffusion through a permeable membrane), which is the displacement of juice from prepared cane by counter flow of water, as shown schematically in the figure above. Such a counter flow scheme for diffusers is the most common set-up, consisting of horizontal

---

\(^2\) The preparation index gives the percentage of open cells in the cane.

\(^3\) In Brazil, the prices offered by utilities have generally not been sufficient to justify the replacement of steam turbine drives by electric motors, i.e. private investors do not find it economic at these prices to optimise factory energy/process efficiency for purposes of cogeneration.
bed diffuser (e.g. De Smet, BMA⁴ or Fairy Mead) and represents more than three quarters of the existing units in the world.

Since the juice is displaced from the cane by diffusion and leaching, it is extremely important that the cane be well-prepared with respect to size reduction and rupture of 92% to 94% of the juice storage cells. Therefore, the use of heavy duty shredders, such as the Tongaat type, is mandatory. The prepared cane bed (that has a thickness from 1 to 1.5 meter) moves along the diffuser on a perforated plate, which is pushed by chain driven flat bars in a closed circuit. Alternatively, in De Smet diffusers, the whole perforated plate moves and conveys the cane. The juice is dumped on top of the bed from reservoirs (so-called distributors located above the bed). After percolating through the bed, the juice goes to the collecting tanks located at the bottom of the diffuser and is then pumped to the next upstream distributor. This way, the juice goes through the bed, moving counter flow with it in several stages. Each stage consists of a distributor, a collecting tank, a centrifugal pump and other accessories.

The juice volume inside the diffuser must be such that the liquid level and bed level coincide, maintaining the bed always saturated with liquid, and avoiding unwanted mixing due to above surface flow (in case of high level) and the formation of air pockets that reduces the contact between fibres and liquid; in both cases a lower extraction efficiency will occur. Sometimes, the cane is first sent to one set of mills for primary extraction of around 65 to 70% of sucrose and, subsequently, the diffuser extracts the remaining sugar from the residual bagasse. When one or two mills are installed upstream of the diffuser, the arrangement is called a bagasse diffuser.⁵ Alternatively, in full cane diffusers, prepared cane can be fed directly to the diffusers. The bagasse leaving the diffuser contains around 85% of moisture, which has to be reduced to about 48–52% by one or two sets of dewatering mills, which also contribute to the sucrose extraction process, before it can be sent to the furnace of the boiler house for energy generation.

The operating temperature inside the diffuser is normally around 70-75°C; this value is determined as a compromise between temperatures necessary to inhibit microorganism growth and temperatures needed for maintaining sucrose inversion at a low level.⁶

For the efficient working of a diffuser, the cane feed rate, cane preparation index, diffuser speed-bed depth and dilution water rate should be controlled (Payne, 1982). Much of this control is influenced by the percolation rate through the cane bed, which is influenced by cane characteristics, cane preparation and the quantity of soil in cane.

A well operated diffuser can achieve an extraction efficiency of 98% or above and a very clean mixed juice, as the cane bed works as a filter; the resulting bagasse has a

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⁴ BMA is the short name for a German engineering company Braunschweigische Maschinenbauanstalt AG.
⁵ A diffuser without upstream mills can perform just as well as one with mills, but needs to be bigger in that case.
⁶ Practices differ though e.g. South African diffusers are always operated at above 75°C, usually 80–90°C. The experience in South African mills has shown that there is negligible difference in inversion between 75 and 85°C. This is mainly because the average residence time for sugar in a diffuser is only about 10 minutes, because most of it is removed in the initial stage, hence the small effect of temperature. The average residence time of bagasse is much longer—about 90 minutes.
higher ash content, and the boiler design, operation and maintenance must take this into consideration.

With respect to energy consumption, the diffuser has several advantages as compared to the milling option. It uses low pressure steam (2.5 bar) at a rate around 1.1 kg steam/tc, and around 20% less mechanical/electrical power than a 6 mill tandem. Diffusion actually uses more steam than milling; however, it is low pressure steam, thereby enabling more of the high pressure steam to be used for electricity generation. Consequently, where electricity generation is to receive high priority, a diffuser may be preferred to milling in such configurations.

2.1.3. **Boiling house**

The juice extracted from the milling department is a turbid greyish/green liquid, which consists of a solution of sucrose mixed with soluble and insoluble impurities. The purpose of the boiling house is to remove the maximum amount of impurities by clarifying the juice with help of heat and lime that cause the flocculation and coagulation of many impurities, which are then separated from the clear juice by settling in a clarifier. The outcome of the clarification process consists of a clear juice that moves to the next process, and of an underflow called mud. Mud is a thick fluid suspension of precipitated impurities in clear juice. The clear juice must be recovered in a modern and efficient factory. Filtration is thus performed by rotary vacuum filters which separate the solid impurities from the juice to facilitate economic disposal of solids, and to recover as far as possible the sucrose in the mud.

After removal of impurities from the raw juice, which would otherwise interfere with subsequent processing, the next step is to remove the water, which is about 80% of the juice by weight. This concentration process is performed in the boiling house over two stages—evaporation and sugar boiling. Evaporation produces syrup by concentrating clear juice. This is performed in multiple-effect evaporator vessels. Sugar boiling, or crystallization, starts in vacuum pans. At this stage the syrup is evaporated until it reaches super saturation state, i.e. when crystals begin to form in the syrup. At this point, the crystallization process is initiated and the evaporation is allowed to proceed until the maximum concentration is achieved, yielding a semi-solid suspension of sugar crystals in mother liquor called massecuite. After discharge of massecuite from the vacuum pan, further growth of the crystals takes place in open vessels of semi-cylindrical shape known as crystallisers. The massecuite is stirred and cooled to crystallise the recoverable sucrose remaining in solution, thereby further exhausting sugar from the molasses.

The next step is to separate the sugar crystals from the mother liquor using centrifugal machines. The crystals are washed with water and steam to achieve the required polarisation (purity).

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7 Massecuite is a mixture of liquor (or molasses) and crystals
8 The centrifuge consists of a spindle, with a perforated basket connected to it, which is rotated inside a housing. A screen inserted inside the basket keeps back the crystals, but allows the mother liquor to pass through the holes or slots, to be caught in the fixed housing. The sugar obtained is moist and hot and is passed on for drying. There are two types of centrifugals—batch and continuous. The latter has a conical perforated basket which causes the crystals to move across the screen, and be continuously ejected from the top of the basket by centrifugal force.
Sugar drying is carried out by passing raw sugar in a dryer together with hot air, which absorbs the water from the sugar crystals. The most popular dryer is the rotary drum dryer, set at an angle of 5° to the horizontal, to facilitate movement of sugar from one end to the other. Hot air is fed in a counter-current manner, and sugar crystals are repeatedly lifted and dropped continuously providing both a cooling and drying effect to the crystals. Other types of dryers include the tray type dryer and the fluidized bed dryer.

Raw cane sugar is brown and must be re-dissolved and separately refined to produce white sugar. The refineries may be autonomous but are increasingly incorporated as “back end” refineries within raw sugar factories where energy from bagasse can be used for the refining process. Availability of surplus energy from a sugar factory is strongly influenced by the presence of a back end refinery. The refining stage can be circumvented by using sulphur dioxide to bleach colour from the juice in the ‘raw house’. This ‘sulphitation’ process is used extensively in India but has the disadvantage of leaving potentially high residues of sulphur dioxide in the sugar.

2.2. Comparison of Sugar Cane Characteristics, Mill Process Parameters and Technologies

In order to compare mill performance, several parameters are used. The main objective of this exercise is to identify areas of the mill that deserve more attention with respect to performance. The comparisons should be made with caution since differences in sugar cane quality and varieties, mill equipment age and efficiency and other specific conditions, can distort the results. This is even more important in cases where one tries to compare performance of mills in different countries.

The major performance indicators for sugar mill operation include sugar cane yield, gross season days, capacity utilization, sugar content (or pol) in cane, sugar recovery, fibre content in cane, reduced mill extraction, reduced boiling house extraction, reduced overall extraction, molasses recovery, steam and power consumption for sugar processing and steam generation from bagasse. These performance indicators reflect overall sugar mill efficiency, right from cane cultivation to production of sugar.

Sugar cane yield is the key parameter of cane cultivation efficiency and is extremely important from the view of availability of sugar cane for the mill. The higher the average cane yield achieved, the higher is the cane availability indicating better cane cultivation practices employed by cane growers. The sugar and fibre content in cane depends on a number of factors including cane variety, quantity and timing of water and fertilizer inputs provided, silvicultural treatments, climatic conditions during cultivation, etc. Sugar and fibre content/yield in cane together are the indicators of efficiency of cane cultivation. The higher the sugar in cane, the higher will be recovery prospects of sugar. Normally, high content of sugar and fibre are inversely proportional. The gross season days of operation depend on the cane cultivation practices, type of soil used for cultivation, as well as, climatic conditions.

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9 In most cases, agricultural or field performance indicators, such as cane yield, are not included in the assessment of mill performance. Rather, the actual mill performance parameters are adjusted according to the cane quality, e.g. “reduced mill extraction” rather than “mill extraction,” etc.
Thus the performance of sugar mill operations largely depends on these factors. In view of variations in climatic conditions, soil characteristics, cultivation practices, etc., these factors vary within and across different regions of the world, including the SADC region. Hence the performances of sugar mills also vary across countries and regions.

Table 1: Typical physical performance indicators of selected sugar mills

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Mauritius(^a)</th>
<th>India(^b)</th>
<th>Brazil(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar cane yield (tc/ha/yr(^*))</td>
<td>71.9</td>
<td>64.5</td>
<td>77.0</td>
</tr>
<tr>
<td>Crushing season (days)</td>
<td>116 (Jun-Dec)</td>
<td>100 to 180</td>
<td>210</td>
</tr>
<tr>
<td>Sucrose % cane</td>
<td>12.1</td>
<td>11.5 – 15.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Fibre % cane</td>
<td>15.3</td>
<td>12.5 – 15.0</td>
<td>12.9</td>
</tr>
<tr>
<td>No of mills</td>
<td>11</td>
<td>453</td>
<td>320</td>
</tr>
<tr>
<td>Crushing capacity (TCH)</td>
<td>70 - 275</td>
<td>100 - 150</td>
<td>100 - 1500</td>
</tr>
<tr>
<td>Sugar recovered % cane (average)</td>
<td>10.7</td>
<td>10.4</td>
<td>11.0</td>
</tr>
<tr>
<td>Sucrose % bagasse (average)</td>
<td>1.26</td>
<td>0.50 - 0.75</td>
<td>2.50</td>
</tr>
<tr>
<td>Moisture % bagasse (average,)</td>
<td>48.6</td>
<td>45.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Fibre % bagasse (average)</td>
<td>49.7</td>
<td>48.0</td>
<td>47.0</td>
</tr>
<tr>
<td>Bagasse weight % cane (average)</td>
<td>30.8</td>
<td>30.0</td>
<td>27.4</td>
</tr>
<tr>
<td>Mixed Juice weight % cane (average)</td>
<td>102</td>
<td>90 - 100</td>
<td>100</td>
</tr>
<tr>
<td>Filter cake weight % cane (average)</td>
<td>5.1</td>
<td>3.0 - 3.1</td>
<td>0 – 3.5</td>
</tr>
<tr>
<td>Final molasses weight % cane @ 85 brix (average)</td>
<td>3.0</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>Total sugar recovered % cane (average)</td>
<td>10.7</td>
<td>10.4</td>
<td>12.6(^d)</td>
</tr>
<tr>
<td>Tonnes cane per tonne sugar at 96 pol (average)</td>
<td>9.12</td>
<td>9.65(^e)</td>
<td>8.75</td>
</tr>
<tr>
<td>Milling work imbibition water % cane (average)</td>
<td>33.3</td>
<td>25.0</td>
<td>28</td>
</tr>
<tr>
<td>Milling work imbibition water % fibre (average)</td>
<td>218</td>
<td>167 - 200</td>
<td>223</td>
</tr>
<tr>
<td>Reduced mill extraction (average)</td>
<td>97.5</td>
<td>96.0</td>
<td>96.5</td>
</tr>
<tr>
<td>Pol in open cells</td>
<td>87 – 89</td>
<td>80 - 85</td>
<td>88</td>
</tr>
<tr>
<td>Sucrose lost in bagasse % cane (average)</td>
<td>0.39</td>
<td>0.75</td>
<td>0.7</td>
</tr>
<tr>
<td>Sucrose lost in filter cake % cane (average)</td>
<td>0.07</td>
<td>0.06</td>
<td>1.0</td>
</tr>
<tr>
<td>Sucrose lost in molasses % cane (average)</td>
<td>0.91</td>
<td>1.10</td>
<td>-</td>
</tr>
<tr>
<td>Total losses % cane (average)</td>
<td>1.62</td>
<td>2.00</td>
<td>-</td>
</tr>
<tr>
<td>Reduced Boiling house recovery</td>
<td>88.2</td>
<td>90.0</td>
<td>-</td>
</tr>
<tr>
<td>Reduced overall recovery (average)</td>
<td>86.0</td>
<td>86.5</td>
<td>-</td>
</tr>
<tr>
<td>Boiling house efficiency (average)</td>
<td>98.9</td>
<td>88.0</td>
<td>-</td>
</tr>
<tr>
<td>Steam to bagasse ratio</td>
<td>1.9 - 2.5</td>
<td>2.0 - 2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Steam consumption (kg/tonne cane)</td>
<td>325 - 550</td>
<td>420 - 480</td>
<td>450-550</td>
</tr>
<tr>
<td>Power consumption (kWh/tonne cane)</td>
<td>28 - 32</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>Excess power generated (kWh/tonne cane)</td>
<td>30 - 126</td>
<td>30 - 130</td>
<td>0 - 60</td>
</tr>
</tbody>
</table>

\(^a\) Average technical results of raw sugar mills over the years 1993-2002 (Source: MSIRI, 2003)
\(^b\) Average technical results of 453 sugar mills in India during 2002-2003 season (Source: STAI, 2003)
\(^c\) Total sugars will include sugars other than sucrose where ethanol production is involved, as in Brazil.
\(^d\) Technical results of raw sugar mills in Brazil found in Centre-South and North-North East.
\(^e\) Indian sugar mills produce direct consumption plantation white sugar of 99.8 polarization.
\(*\) Actual yields at harvest are adjusted according to duration of the growth cycle.

All other parameters reflect the operating efficiency of the sugar mill. Final sugar recovery is the key parameter which indicates the amount of sugar recovered as a percent of sugar entering the mill. The difference between cane sugar content and recovered sugar from the cane represents the sugar losses in other co-products of the
sugar mill operation, particularly in the bagasse, molasses or press mud. Reduced mill extraction represents the extraction efficiency of the cane milling section adjusted according to the quality of cane; extraction represents the fraction of juice extracted per unit of cane crushed. The higher these parameters, the higher will be the final sugar recovery.\(^\text{10}\)

Reduced boiling house extraction and molasses recovery are the parameters indicating efficiencies of the boiling house section and crystallizer section respectively. Steam and power consumption for sugar processes are also important parameters for overall mill operation, as well as, for cogeneration power projects. They indicate the energy efficiency of the sugar mill. The capacity utilization is also another parameter which indicates the overall performance of the sugar mill operation. It is a ratio of actual cane crushed per unit time against the installed crushing capacity of the sugar mill. The steam generation ratio indicates the efficiency of the boiler house. This parameter is also very important for energy efficiency and cogeneration power projects.

The operating parameters of the sugar mill also vary within the SADC region, as well as, across other world regions due to different qualities of cane and different operating mill performance. Table 1 (previous page) illustrates the physical performance indicators for sugar mills in three continents in the world, namely, Mauritius (Africa), India (Asia) and Brazil (South America). Table 2 (next page) illustrates selected physical performance indicators for sugar mills in four SADC countries, namely, Malawi, South Africa, Swaziland and Zimbabwe.

2.3. **Benchmarks for Sugar Industry**

Benchmarks are very important comparative performance measurement parameters that indicate the level of performance of a factory against industry standards. In the sugar cane sector, benchmarks need to be established both for the agricultural (sugar cane production) and industrial (sugar cane processing) areas; in this report only industry will be covered. When establishing the benchmarks for a specific mill, attention is paid to the characteristics of the factory with respect to maximum capacity of each processing stage, level of automation, quality of the raw material (sugar cane) and technology status/condition (obsolescence, maintenance and operators training). For example, a four mill tandem cannot match the performance of a six mill tandem, in terms of extraction efficiency and throughput. However, high mill performance standards can be established as long term goals/targets and mills can then assess how far they are from best practice, and which areas deserve close attention.

Overall performance in the sugar industry is defined by what is known as the industrial efficiency. For a sugar mill, the industrial efficiency index is the total sucrose in the produced sugars as a fraction of the total sucrose of the milled cane. This is further discussed in section 4.5.2 with reference to Brazilian sugar mills.

\(^\text{10}\) Extraction is related to the milling section, whereas recovery is related to overall factory performance.
Table 2: Typical physical performance indicators of sugar factories

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Malawi</th>
<th>South Africa</th>
<th>Swaziland</th>
<th>Zimbabwe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar cane yield (T/ha/yr)(^b)</td>
<td>105</td>
<td>59.4</td>
<td>93.8</td>
<td>97.7</td>
</tr>
<tr>
<td>Sucrose % cane</td>
<td>13.8</td>
<td>13.0</td>
<td>14.0</td>
<td>13.9</td>
</tr>
<tr>
<td>Fibre % cane</td>
<td>15.3</td>
<td>14.9</td>
<td>13.8</td>
<td>14.6</td>
</tr>
<tr>
<td>No of mills</td>
<td>2</td>
<td>15</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Average crushing capacity (TCH)</td>
<td>215</td>
<td>304</td>
<td>313</td>
<td>455</td>
</tr>
<tr>
<td>Crushing capacity (range - TCH)</td>
<td>160 - 300</td>
<td>90 - 550</td>
<td>270 - 360</td>
<td>400 - 500</td>
</tr>
<tr>
<td>Sucrose % bagasse</td>
<td>1.23</td>
<td>1.00</td>
<td>1.35</td>
<td>1.39</td>
</tr>
<tr>
<td>Moisture % bagasse</td>
<td>48.4</td>
<td>51.0</td>
<td>50.4</td>
<td>50.2</td>
</tr>
<tr>
<td>Fibre % bagasse</td>
<td>49.4</td>
<td>47.1</td>
<td>47.3</td>
<td>47.7</td>
</tr>
<tr>
<td>Bagasse weight % cane</td>
<td>30.5</td>
<td>31.1</td>
<td>28.7</td>
<td>30.1</td>
</tr>
<tr>
<td>Mixed Juice weight % cane</td>
<td>111.5</td>
<td>121.5</td>
<td>119.0</td>
<td>119.4</td>
</tr>
<tr>
<td>Filter cake weight % cane</td>
<td>1.36</td>
<td>2.67</td>
<td>2.71</td>
<td>1.43</td>
</tr>
<tr>
<td>Final molasses weight % cane @ 85 brix</td>
<td>4.24</td>
<td>4.06</td>
<td>3.75</td>
<td>3.94</td>
</tr>
<tr>
<td>Milling work imbibition water % fibre</td>
<td>278.8</td>
<td>357.5</td>
<td>354.8</td>
<td>344.3</td>
</tr>
<tr>
<td>Reduced mill extraction</td>
<td>96.8</td>
<td>97.6</td>
<td>96.7</td>
<td>96.9</td>
</tr>
<tr>
<td>Preparation index</td>
<td>90.2</td>
<td>89.1</td>
<td>91.1</td>
<td>91.7</td>
</tr>
<tr>
<td>Sucrose lost in bagasse % sucrose in cane</td>
<td>2.84</td>
<td>2.28</td>
<td>2.64</td>
<td>2.72</td>
</tr>
<tr>
<td>Sucrose lost in filter cake % sucrose in cane</td>
<td>0.15</td>
<td>0.23</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>Sucrose lost in molasses % sucrose in cane</td>
<td>11.59</td>
<td>9.98</td>
<td>7.71</td>
<td>8.48</td>
</tr>
<tr>
<td>Lower Calorific Value of bagasse (kJ/kg)</td>
<td>6923</td>
<td>6902</td>
<td>7150</td>
<td>7704</td>
</tr>
</tbody>
</table>

\(^a\) Average technical performance of sugar mills over the years 1993-2002 (Source: SMRI, 2003)
\(^b\) Source: FAOSTAT, 2004

2.4. Best Practices and Technologies for Raw Sugar Manufacture

Raw sugar production is a mature process. Opportunities for new technology development are limited, although prospects still exist for process innovation and optimisation, especially related to improved productivity. Most SADC countries face financial constraints to invest in novel technologies, but opportunities exist for process optimisation and improved productivity through efficient use of resources, including energy, and equipment design. The potential of some new technologies and best practices for each stage in sugar processing is outlined in the following paragraphs:

**Milling Department**

Two-roller milling units are one of the more recent innovations, and have been used in Australia, India and Mauritius. Comparable extraction efficiency can be obtained as with three roller mills, but their main benefit is their lower power consumption. The use of electrically driven hydrostatic drives simplifies mill operations and allows easier mill maintenance than a traditional steam turbine; such equipment is generally a good investment where cogeneration is practised (SASTA, 2002). \(^{11}\)

**Clarification**

Rotary vacuum filters for underflow treatment is the preferred technology in raw sugar factories. Some sugar technologists suggest eliminating the filters completely and using instead a mat of shredded cane in a diffuser to recycle the underflow. The

\(^{11}\) Conversely, where high sugar extraction is important and cogeneration is not an option for some reason, the two-roller milling units are unlikely to be adopted (Purchase, 2007).
results of trials in South Africa showed that this recycling technique has no adverse effect on extraction and on bed percolation, and does not result in additional sucrose loss in the diffuser (Clarke, 1999).

The most intensely discussed technology is membrane filtration, expected to replace the standard clarification techniques and lead to improved sugar quality, as well as, increased recovery. Other claimed benefits include reduced evaporator scaling, juice sterilization, and increased utilisation of downstream equipment. However, this is yet to be demonstrated on a commercial scale; there are questions still on its reliability and high operating costs.

Evaporation
Most sugar factories use forward feed, four or five effect, short-tube rising film or Roberts evaporator, with vapours bled from the first two or three effects for juice heating and vacuum pans. Five effects evaporation has proven to be the most efficient from Mauritian experience.

The most promising technology for steam savings in the evaporator station is the use of long-tube, falling-film (LTFF) evaporators. The primary advantage of LTFF evaporators is the higher juice flow velocity, which both enhances heat transfer and shortens juice residence times. LTFF evaporators are quite common in the beet sugar industry and are being experimented in the cane sugar industry. Research shows that in an efficient factory, the evaporator station acts as a boiler to supply low pressure steam for heating and concentration of juice in the boiling house, while the main boiler is used for supplying high pressure steam for electricity generation.

Crystallization
Continuous vacuum pans offer advantages both in the stability of steam demand and overall steam requirement. They also have increased capacity, reduced sugar losses, and are easier to control. On the other hand batch pans need a longer time to get the equipment in operation, and it is necessary to empty the equipment during the weekly shutdown (Rao, 2001). Batch pans are nevertheless still widely used since improvement in productivity of batch pans can be done by improved circulation, improved feed quality and instrument control.

Centrifugation and Sugar handling
Batch centrifugals have become much larger and energy efficient but the major development has been in the use of continuous centrifugals for high-grade sugar. There are problems of reliability at high throughput, lump formation and crystal breakage which need to be resolved for continuous centrifugals to become widely accepted for high-grade sugar.
3. Fibre Resources

3.1. Fibre Resources from Sugar Cane

Bagasse is the fibrous residue leaving the last mill of a milling tandem or diffuser of the milling unit of a sugar factory. It is a mixture of hard fibre, with soft and smooth parenchymatous (pith) tissue which is highly hygroscopic. Bagasse contains chiefly cellulose, hemicellulose, pentosans, lignin, sugar, wax, and minerals. The detailed composition of bagasse is given in Table 3.

The quantity of bagasse obtained from cane processing varies from 22 to 36% of cane and is affected mainly by the cane fibre content and the cleanliness of cane supplied, which in turn depends on the harvesting practices.

Table 3: Composition of bagasse

<table>
<thead>
<tr>
<th>Component</th>
<th>% (dry basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical components in bagasse</strong></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td>26 - 43%</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>17 - 23%</td>
</tr>
<tr>
<td>Lignin</td>
<td>13 - 22%</td>
</tr>
<tr>
<td><strong>Average composition of mill wet bagasse</strong></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>46 - 52%</td>
</tr>
<tr>
<td>Fibre-pith</td>
<td>43 - 52%</td>
</tr>
<tr>
<td>Sugar</td>
<td>2.5%</td>
</tr>
<tr>
<td>Minerals</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Ultimate analysis of bagasse</strong></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>47%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.5%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>44%</td>
</tr>
<tr>
<td>Ash</td>
<td>2.5%</td>
</tr>
<tr>
<td><strong>Gross calorific value (kJ/kg)</strong></td>
<td></td>
</tr>
<tr>
<td>@ 48% moisture content</td>
<td>9,950</td>
</tr>
<tr>
<td>Dry basis</td>
<td>19,250</td>
</tr>
</tbody>
</table>

*Source: Cortez and Gómez, 1998*

The gross calorific value of bagasse is 19,250 kJ/kg at 0% moisture and 9,950 kJ/kg at 48% moisture. The net calorific value or the practical energy that can be derived from bagasse is 7,985 kJ/kg at 48% moisture content. Hence, percentage moisture content of bagasse is the most significant parameter that determines its calorific value. Bagasse contains 45-52% moisture as it comes out of the milling plant, and is generally known as “mill wet bagasse”. Thus, the lower the moisture content, the higher the bagasse calorific value. A good milling process will result in a low bagasse moisture content of 45%, whereas 52% moisture would indicate poor milling efficiency. Most mills produce a bagasse of 48% moisture content and as such most boilers are designed to burn bagasse with around 50% moisture. Generally, bagasse provides most of the energy needs of sugar factories. After exiting the milling tandem
or the dewatering mills of the diffuser system, bagasse is transported by conveyors and fed directly to the boilers.

Apart from moisture, bagasse also contains an equivalent proportion of fibre (cellulose), the components of which are carbon, hydrogen and oxygen, some sucrose (1-2%), and ash originating from extraneous matter brought together with cane delivered to the factory. Extraneous matter content is higher with mechanical harvesting, which subsequently results in lower calorific value.

Bagasse is difficult to store and is prone to fermentation and chemical reactions that can trigger slow internal combustion resulting in fire risks. There is also a loss in its sugar content which ultimately results in a drop in its calorific value. Bagasse can be stored up to a period of one year if it is dried to a moisture content of less than 30%. Bagasse drying is generally not practiced in the sugar industry and is currently an area of research and development.

Bagasse has a low bulk density of 130 kg/m³ which poses handling and storage problems. Hence, it has historically been common practice to continuously burn bagasse obtained from the mill in order to avoid disposing it in stacking areas, which is costly in terms of equipment and facilities. Any excess bagasse generated is stored in the open or under covered areas for use during weekend shut downs or during off crop season to produce steam and electricity for factory use, as well as, for export to the public grid.

The proximate and ultimate analysis of mill-wet bagasse is as shown in Table 4.

### Table 4: Analysis of mill-wet bagasse

<table>
<thead>
<tr>
<th>Proximate analysis (%)</th>
<th>Ultimate analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed carbon</td>
<td>11.5</td>
</tr>
<tr>
<td>Volatile</td>
<td>37.0</td>
</tr>
<tr>
<td>Moisture</td>
<td>50.0</td>
</tr>
<tr>
<td>Ash</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. Introduction to Cogeneration

Cogeneration is defined as the concurrent generation of process heat and electrical power in an industrial plant by the sequential use of energy from a common fuel source. Depending on the quality of process heat required, cogeneration may be based on the topping or the bottom cycle (see Figure 4).

- **In the ‘bottom cycle’,** the required process heat is at high temperatures and hence power is generated through a suitable waste heat recovery system.

- **In ‘topping cycle’,** the required process heat is at low temperatures and therefore, power generation is performed first. All sugar mills employ this cycle for cogenerating power and heat.

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12The calorific value per unit mass of bagasse goes up as sugar is removed. The total energy content of stored bagasse however, goes down.
Installation of high-efficiency cogeneration systems results in the following benefits:

- An efficient cogeneration system provides a stable and reliable power supply for the sugar mill and thus allows uninterrupted manufacturing.
- Power generation using bagasse is environmentally cleaner, as bagasse produces very little fly ash and no sulphur oxides.
- The net contribution of greenhouse gases from a bagasse-based cogenerating plant is zero, since the carbon dioxide absorbed by the sugar cane grown exceeds what is emitted by the cogenerating plant.
- A bagasse-based installation has much lower installation period (18-24 months), compared to 96-120 months required for a typical coal-based power unit.
- A bagasse-burning power plant requires a lower capital investment and lower running costs compared to equivalent fossil-based power plants.
- Such a power plant has less impact on the landscape and the environment compared to coal or other fuels, as it is already available at the sugar factory, and does not involve mining, extraction, or long-distance transportation.
- The rural location of sugar mills facilitates distributed generation, i.e. cogenerated power can be directly fed to local sub-stations, thus minimizing transmission and distribution losses and the provision of long feeder lines.
- Cogeneration systems provide low-cost electricity compared to most conventional options, even before considering external costs of conventional fossil alternatives.
- No expenditure is incurred for the safe storage and disposal of bagasse.
- A cogeneration plant has no extra overheads and places minimal administrative burdens on the sugar factory as it fits into existing management structures of the sugar factory.
- It allows the sugar industry to diversify from the traditional practice—where raw sugar is the only commercial product—into electricity generation and trade.
- It provides incentives for sugar mills to conserve energy and reduce steam consumption, thereby improving the profitability of the operation.
- The generation of surplus power in sugar factories is ideally suited for rural
electrification and for energizing irrigation pumps and industrial and agro-based businesses in the villages.

- Among renewable energy initiatives, sugar is one of the few sectors where most of the basic infrastructure already exists.
- There are no skill shortages to implement cogeneration projects since the technical staff of sugar mills are quite conversant with generation of power.

3.3. Status of Bagasse Utilisation in SADC Countries

The high levels of bagasse availability in SADC countries provide a readily available source of biomass for cogeneration plants and other fibre-based applications, which can generate additional revenue and resource streams for the sugar company and/or its affiliated companies. The initiation of biomass cogeneration will nevertheless require that proper infrastructure, and policy measures are in place to facilitate independent (i.e. non-utility) power and heat production. Some countries like Zimbabwe and Swaziland have bagasse availability comparable to that of Mauritius, while South Africa has around six times as much. Thus with proper bagasse energy development programmes, as has been the case in Mauritius, bagasse biomass energy can be successfully tapped. Table 5 gives the estimated availability of bagasse in SADC countries.

Table 5: Estimated Potential Availability of Bagasse in SADC Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Bagasse availability Notes (thousand tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angola</td>
<td>104</td>
</tr>
<tr>
<td>DR Congo</td>
<td>212</td>
</tr>
<tr>
<td>Malawi</td>
<td>611</td>
</tr>
<tr>
<td>Mauritius</td>
<td>1,290</td>
</tr>
<tr>
<td>Mozambique</td>
<td>149</td>
</tr>
<tr>
<td>South Africa</td>
<td>8,303</td>
</tr>
<tr>
<td>Swaziland</td>
<td>1,862</td>
</tr>
<tr>
<td>Tanzania</td>
<td>370</td>
</tr>
<tr>
<td>Zambia</td>
<td>685</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>1,902</td>
</tr>
<tr>
<td>Total</td>
<td>15,488</td>
</tr>
</tbody>
</table>

Source: WEC (2001)

^1 based on a yield of 3.26 tonnes of fuel bagasse @ 50% moisture content per tonne sugar produced.

Except for Mauritius, most SADC countries have little experience with bagasse cogeneration beyond the needs of the factory. Most sugar factories in the region concentrate upon generation of electricity for their own captive consumption to either supplement or replace supplies from the grid. The efficiency of electricity generation in these mills is poor due to the rudimentary technologies that operate with low steam pressure and temperature. Moreover, the historical abundance of fossil alternatives such as coal and large-scale hydro has hampered the development of cogeneration on a large scale for electricity export and reduces national interest in such ventures. The traditional reliance on imported coal and large-scale hydro has more recently been decreased, as the benefits of more diversified and decentralised energy systems are being recognised in the region.
A number of pilot projects have nevertheless been initiated with limited success. In Zimbabwe for example, the two sugar factories at Triangle Sugar Limited and Hippo Valley Estates produce electricity from bagasse to meet their electricity requirements for irrigation, sugar processing and to supply the local community, which is composed mainly of the employees of the sugar companies. Coal is used as a supplementary fuel in electricity production [Mbohwa and Fukuda, 2003]. The plants at the two mills currently produce a total 61 MW but the potential is estimated to be 150 MW if more efficient technologies are implemented. Hippo Valley Estates exported some electricity to the grid on a trial basis for approximately one year but the electricity price offered was somewhat low for providing a good return on investment.

Bagasse accounts for most (33%) of the energy supply in Swaziland. It is used to produce steam and electricity for running the sugar plants, and the electricity is also distributed to company facilities and staff houses. Swaziland produces a mean annual total of 560,000 bone-dry tonnes of bagasse from the three sugar mills. Although the bagasse is used for cogeneration, there is no export of power to the public grid. In 1999, Ubombo, Mhlume and Simunye sugar mills and the pulp industry together produced 264 GWh, about 27% of the electricity consumed in Swaziland. Low efficiency conversion techniques are presently used and there are few incentives for the Swaziland sugar mills to develop the technology (ECS, 2002).

South Africa meets around 90% of the energy demand in its sugar industry from bagasse, but most of the bagasse is burnt in inefficient boilers. With the sugar mills currently generating a significant amount of power for own use and limited export, bagasse offers some of the greatest potential for independent power production in South Africa, using renewable resources. Estimates show that the current electricity production of energy of 30 kWh/mtc can be increased by up to 120 kWh/mtc using conventional steam plants running at higher pressures. Using integrated gasification and combined cycle combustion technologies, the energy yield can be increased up to 200 kWh/mtc. By increasing efficiency and introducing new technologies, the potential of this resource can be increased from the current 210 GWh to 1,400 GWh per annum (DME, 2003).

3.4. Review of Bagasse Cogeneration Technologies

3.4.1. Technologies for cogeneration

1) Extraction cum back pressure route
The main features of this configuration (see Figure 5) are listed below:
- The sugar factory produces only as much steam as is needed for its processes.
- By upgrading the steam parameters, surplus power is produced after meeting captive requirements.
- Surplus power production is envisaged only during the crushing season.
- This is the cheapest option from the point of view of initial cost and efficiency of the system.
- This turbine, however, has the disadvantage that surplus power supply is not stable and affected by fluctuations in cane supply, process steam demand, etc.
2) **Extraction and Condensing Route**

This system (see Figure 6) has the following features:

- The sugar factory produces steam by optimising the entire quantity of bagasse produced during the crushing season.
- By using an extraction and condensing turbine, surplus power production can be extended during the off-season by operating the turbine in the condensing mode, provided off-crop season fuel is available abundantly and cheaply.
- Power can be generated by using bagasse brought from nearby sugar mills or by using bagasse left over during the latter part of the crushing season.
- The capital cost is higher for this technology.
- This system ensures the supply of stable surplus power during the crushing season thereby reducing fluctuations in sugar plant operation.
3) Condensing Route based on Dual Fuel System

This option (see Figure 7) allows a year-round, stable surplus power supply through the use of a support fuel. Its main features are listed below:

- This is a viable option for sugar mills located near a source of secondary fuel (or where procurement costs of such a fuel are not high).
- The reliability of the alternate fuel supply has to be ensured.
- The boiler design should incorporate a suitable furnace capable of multi-fuel combustion, particularly the combination of bagasse and coal/lignite.
- The capital cost of multi-fuel systems is high, particularly those using coal as support fuel, in addition to costs associated with pollution control and ash disposal.
- Highly skilled manpower is required for the operation and maintenance of such an advanced technology.

Figure 7: Condensing route based on dual fuel system

In addition to the options outlined above, the following simple energy conservation measures, if adopted, can contribute to surplus power generation:

- Replacement of turbo drives used for cane preparation and milling with hydraulic or electric drives.
- Reduction of process steam consumption from prevalent levels (50-55% on cane) to 42-45% by modifying the juice heating and evaporation system.
- Increasing the efficiency of boiler operations from the existing average of 60% to the minimum stipulated value of 70%.
- Introduction of more controls and instrumentation in power plant operations.
- Use of bagasse driers with proven technology to reduce the moisture content of bagasse before it is burnt in the boilers.

To derive maximum power from a cogeneration system, it is necessary to ensure maximum energy economy and optimum system configuration. This also ensures high efficiency at minimum costs and adequate safety. Modular standardization of capital equipment and reuse of displaced capital plant elsewhere can substantially reduce the cost of upgrading cogeneration facilities in the existing plant.
3.4.2. **Prime technology for cogeneration**

The prime technology for sugar mill cogeneration is the conventional steam – rankine cycle design for conversion of fuel into electricity. A combination of stored and fresh bagasse is usually fed to specifically designed boilers to generate steam at typical pressures and temperatures of more than 40 bars and 440°C, respectively. The high pressure steam is then fed either to a back pressure/single extraction back pressure, or single extraction condensing/double extraction cum condensing type turbo generator operating at similar inlet steam conditions. The back pressure or extracted steam from the turbine is used for providing steam requirements for sugar processing, other by-products and for cogeneration equipment like high pressure heaters, de-aerators, soot blowers, etc.

Due to the high pressure and temperature, as well as extraction and condensing modes of the turbine, higher quantum of power gets generated, over and above the power required for the sugar mill and its ancillary operations. The excess power generated in the turbine generator set at typically 11 kV is stepped up to high voltages of for instance 66, 110, or 220 kV, depending on the nearby substation configuration, and fed into the nearby utility grid through such a substation.

As the sugar industry operates seasonally, the boilers are normally designed for multi-fuel operations, so as to utilize mill bagasse, procured bagasse / biomass, coal and fossil fuel (in exigencies), and to ensure year round operation of the power plant and allow electricity export to the grid. Normally, due to captive requirements of steam and power, the exportable surplus during cane crushing season is lower compared to the off-season period.

3.4.3. **Evolution of technology**

The electric power generation technology using solid fuels and the rankine cycle is conventional and being applied by the power industry worldwide. To use this technology for power generation in sugar mills, some basic alterations are required to facilitate different types of fuels. The peculiarities of bagasse/biomass and combination with fossil fuels, including moisture content, density, and specific storage/transport and handling requirements generally have to be taken into account during design of the firing grate in the boiler. All other technologies and equipment are similar to the conventional power plants that are fired by solid fuels.

Conventional power plants use extra high pressures up to 87 bars or even more. Initial configuration changes in bagasse-fired cogeneration power plants in sugar mills started by increasing pressure to 40 bars and later on to 60 bars. Higher pressure normally generates more power with same quantity of bagasse or biomass fuel; hence to enhance opportunities for exportable surplus from such power plants, increasing the pressure and temperature configuration became important. In India, 67 bars pressure and 495°C temperature is now established operational parameters for sugar mill cogeneration plants over the last 7 years. Facilities with extra high pressure at 87 bars and 510°C temperature is already being established and there are about ten such projects commissioned and operating in India. The average increase of power export from 40 bars to 60 bars can be as high as 100 to 150%, while further increases from 60 to 80 bars stages is in the range of 7-10%.

Cogeneration technology development is successful in Mauritius, India and Brazil because local expertise is available for design, manufacture, construction, operation
and maintenance of bagasse/biomass/fossil fuel fired sugar mill cogeneration power plants.

**New technologies for bagasse cogeneration**

Condensing Extraction Steam Turbine (CEST) cogeneration technology is the commercial state-of-the-art technology currently available in the market. CEST technology generates more electricity per unit input of fuel compared to traditional boilers. The major drawback of the condensing steam turbine is the high unit operating cost of the technology at small scales (50-60 MW) and has historically depended for viability on the low cost of feedstock biomass fuel (such as that available at a sugar mill, where bagasse has been considered as “free”) (Carpentieri et al., 1993)\(^\text{13}\).

A promising alternative to steam turbines are gas turbines fuelled by gas produced by the thermo-chemical conversion of the biomass. The exhaust is used to raise steam in heat recovery systems:
- process heating needs in a cogeneration system;
- for injecting back into the gas turbine to raise power output and generating efficiency in a steam-injected gas turbine cycle (STIG), or;
- expanding through a steam turbine to boost power output and efficiency in gas turbine/steam turbine combined cycle (GTCC).

Gas turbines, unlike steam turbines, are characterized by lower unit capital costs at modest scale, and the most efficient cycles are considerably more efficient than comparably sized steam turbines.\(^\text{14}\) Other variants also exist like the biomass integrated gasifier/gas turbine (BIG/GT) on which much development work is still being done.

A recent project developed by Copersucar Technology Center (CTC)\(^\text{15}\) has shown the technical feasibility of harvesting green cane, recovering part of the trash and using this trash and the bagasse as the only fuel for a gasification system integrated with a combined cycle (BIG-CC). It has been estimated that enough trash could be recovered, under average conditions, at a cost of around US$1/GJ.

The estimated investment costs of the BIG-CC plant of capacity 30MW were too high; the resulting electricity production cost of around US$74/MWh was considered

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\(^{\text{13}}\) To be able to use condensing/extraction turbine generators, the power plant must operate all year round, process steam consumption need to be reduced from (the existing average condition in Brazil) of the 500 kg steam/TC to less than 350 kg steam/TC. This way a balance is obtained between the high pressure steam and process steam demands. The substitution of steam turbine drives by electric motor drives for the main equipment may also be necessary.

The reduction of high pressure steam consumption to the 350 kg/TC level can be often accomplished by replacing the auxiliary equipment steam turbine drives (feed water pumps, exhaust fans, etc.) with electric motors. Replacing the shredder and knives turbine drives by efficient electric motors, the high pressure steam demand can be reduced to around 280 kg/TC. If the electricity tariffs are attractive (like in Mauritius), the steam turbine drives of the mills can be replaced by electric motors with inverters (for speed control) that allows a more efficient use of the high pressure steam, thus increasing the kWh/TC available for sale. In India, six sugar factories have reduced their steam consumption to 35% on cane by introducing energy conservation measures, and 25 more sugar mills are introducing the same measures to reduce the steam consumption.

\(^{\text{14}}\) Gas turbine combined cycles operate at an efficiency of 45-50%, whereas steam turbines cycles generally operate at 30-40%.

\(^{\text{15}}\) CTC is now known as the Sugar cane Technology Center.
too high for the Brazilian situation. Since this would have been the first plant of its kind, these high costs could be considered justifiable and were expected to come down with technological learning. However, no investor was willing to host the plant, despite the promised assistance from the World Bank, which was interested in providing enough funds to make the project economically viable. Therefore, the project was terminated without the construction of the first cogeneration plant in a mill based on the BIG-CC technology (CTC, 2005).

Experience of Mauritius in cogeneration

In Mauritius, there are currently 11 operational sugar factories having crushing capacities ranging from 75 to 310 tonne cane per hour (TCH). Surplus electricity is generated in all the sugar factories except in the mill with the lowest crushing capacity (which is only self-sufficient in energy). Three firm power plants operate throughout the year by using coal as a complementary fuel during the off-crop season, whereas the remaining seven factories are continuous power producers, generating electricity from bagasse during the crushing season. The total installed generation capacity within the sugar industry is 243 MW, out of which 140 MW is firm power capacity. Around 1.8 million tonnes of bagasse is generated on an annually renewable basis and an average of around 60 kWh per tonne of cane crushed is generated for the grid throughout the island. Figure 8 shows the amount of electricity exported per tonne of cane/fibre in sugar factories operating at different boiler pressures.

Figure 8: Electricity generated per tonne of cane/fibre from Mauritian sugar factories (2003)

Source: Seebaluck, 2004

In Mauritius, electricity from cogeneration plants (fired with bagasse and coal) has already reached 747 GWh or 38.3% of total generated power as shown in Figure 8. It was only 0.3 GWh in 1957. The total potential from this resource can be achieved upon implementation of additional projects designed to operate at 82 bars using already commercialized state-of-the-art technology. In addition, further improvements
can be made to increase total potential\textsuperscript{16}. It is considered that there is still room for improvement in cane processing for sugar recovery, energy production from bagasse and value added products from various by-products.

**Critical components**

The critical components in sugar mill cogeneration technology include the boiler and its design, the design of travel grate for controlling firing of bagasse, quality of feedstock biomass or its combination with fossil fuel in the boiler. The important elements in boiler design include the super heater design including inlet steam tapping and its operation for control of superheat temperature, design and operation of de-aerators and high-pressure heaters for power cycle optimization and bagasse feeding arrangement. The efficient long-term operation of the boiler is mainly dependent on these critical components.

Bagasse/biomass storage, handling and the boiler feeding system is also extremely important for ensuring continuous and controlled quantities of bagasse/biomass or their combination to the boiler. The conveyor system design from the return bagasse carrier in the sugar mill to the storage yard, and back to the boiler, is also critical. As far as the turbine generator system is concerned, design of the surface condenser and its operation, controls on steam flows and overall turbine operation control system are crucial, considering especially managing the fluctuating steam and power needs for captive operations, and maintaining steady and optimum quantum of exportable power to the grid.

Quality of water fed to the boiler, for turbine cooling and auxiliary equipment is also important, along with the selection of technology (reverse osmosis or conventional de-mineralized water plant). The design and operation of optimum water treatment plant are very crucial, considering that there may be inadequate capacity among the sugar mill personnel to handle such aspects, whose reliability becomes more important for grid-connected power plants. Also, quality control of condensate return and its system design from the boiler, as well as, the first body of the evaporator is extremely important to avoid contamination of juice.

Use of electro-static precipitators (ESP) for particulate emission control becomes almost mandatory for sugar mill cogeneration power plants, in view of existing norms of pollution control and the likelihood of further stringent regulations being stipulated. Bagasse and other biomass fuels are more volatile, and the chances of back firing in the ESP are quite common for these plants. As such, appropriate design and operation of the ESP becomes very critical, along with boiler operation control.

3.5. **Optimizing Bagasse Cogeneration**

3.5.1. **Power generation from sugar factories**

The amount of surplus electricity that can be generated from the sugar industry is highly dependent on the fibre content of the raw material, the efficiency of steam generation and conversion of the thermal energy to electrical power, and on the efficiency of energy (steam, vapour and electricity) use in the sugar manufacturing

\textsuperscript{16} The estimated potential is based on a process steam requirement of 450 kg per tonne cane and an electrical energy requirement of 30 kWh per tonne cane
processes. Improved technology can further enhance the bagasse energy potential, but this comes with added capital costs.

**Factors to be considered at the feasibility stage**

The assessment of surplus electricity production potential from bagasse that can be exported by sugar mills to the public grid requires careful analysis, and must be based on statistical data available over a longer period of time, so that the evaluation is based on solid data. The main factors affecting electricity generation potential are as follows:

- Average volume of production taking into account low and high extreme cases.
- Evolution of the cane characteristics and quality with emphasis on the fibre content, juice and syrup concentration/volume during the crop season.
- Steam/vapour consumption of different sugar making process operations during the normal and transient factory operating mode.
- Electricity consumption of all equipment in the plant during the normal and transient factory operating mode.

**Steam economy in the sugar manufacturing process**

Improvements in steam economy can be achieved in a sugar factory by introduction of the following measures:

1) **Improvement of the calorific value of bagasse**

Bagasse characteristics can be enhanced for the maximum energy generation mainly by reducing the moisture present in the material. It has been estimated that a 1% moisture drop in bagasse is equivalent to an increase of 0.5-1 kWh/tc in electricity production. Lowering of the bagasse moisture content is mostly achieved in the milling department through proper mill setting, optimum roller speed, hot water imbibition, regular feed of well prepared cane to the mill, etc.\(^{17}\)

2) **Energy conservation measures in the milling department**

Firstly, the cane should be well prepared to feed the milling unit with an evenly prepared mat of cane, with a high level of opened cells at a relatively constant rate. In Mauritius, the average cane preparation index is 88 and this process requires around 40% of the energy required for milling.\(^{18}\).

Secondly, a balance is needed between optimising sugar extraction (which depends on the number of rollers and milling units) and optimum energy use which impacts on the amount of electricity generated.\(^{19}\).

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\(^{17}\) Bagasse moisture reduction can be achieved by milling devices such as the Donelly chute, Lotus mill rolls, Maeschert grooves on the first mill (to ensure good drainage of juice), absence of longitudinal grooves on the last mill top roll, and fine radial grooving of last mill rollers. Some good practices are to have heavy hydraulic loading of the mill, optimum running speed and hot imbibition water.\(^{18}\)

\(^{18}\) Milling accounts for around 60-65% of the energy requirement of a sugar factory using milling tandems for juice extraction.

\(^{19}\) Although a higher number of rollers or milling units results in higher juice extraction, it also results in higher power requirement. Research shows that the amount of sucrose that can be extracted from the first mill of a milling tandem is around 92 kg per tonne of cane processed, and subsequently, dropped down to as low as 1.35 kg per tonne of cane processed (Seebaluck, 2003). Concurrently, the power consumption of the individual units varies between 2.3 to 1.7 kW per tonne of cane processed, depending upon the position of the milling units in the milling tandem (Seebaluck, 2004).
3) Water conservation measures at the boiling house
Imbibition water should be optimised during milling with respect to sugar recovery which should lead to less evaporation in the process and hence less steam requirements\(^\text{20}\). A five effect evaporator station is the most optimal configuration for energy economy; sextuple effects are currently being tested on trial basis. Vapour should be bled to juice heaters and vacuum pans as far as the temperature profile allows\(^\text{21}\).

4) Energy conservation measures at the boiler house
The boiler house is an important area for achieving significant fuel savings in a sugar mill, and this unit profoundly affects the performance and availability of the plant. Some of the key measures for enhancing the boiler efficiency thereby achieving the fuel economy are as follows:

- Use of high pressure/temperature boilers with fuel flexibility.
- Set-up of waste heat recovery equipment such as economizers\(^\text{22}\) which maximize condensate recycling.
- Use of air pre-heaters.
- Use of regenerative feed water heating (high-pressure feed water heater, low-pressure feed water heater, and de-aerator).
- Install steam accumulators.
- Optimisation of boiler blow down.
- Adequate lagging of steam piping network (both flanges and pipelines).
- Reduction of the moisture content of bagasse feed to the boilers (every 1% reduction in moisture content increases the boiler efficiency by 0.8%).
- Optimisation of excess air levels to enhance combustion efficiency.
- Flash steam recovery.
- Use of variable frequency drives for fans and blowers in boiler house.
- Operation of the boiler at maximum continuous rating.

5) Optimise boiler draft system
Bagasse fired boilers require forced draft, induced draft, and secondary air fans for meeting the needs of air and waste gas exhausting. All these fans should be designed with a minimum of 15% excess volume rating and 30% excess pressure rating. Aerofoil shaped blades for fans give an optimum efficiency of more than 80%. The induced draft fan drive should have a continuous speed variation facility to always ensure working near the optimum efficiency.

6) Use of instrumentation and control systems
The boiler must be regulated to match the steam output with the process demand, and to achieve this with maximum fuel efficiency. It is therefore necessary to continuously

\(^\text{20}\) Minimisation of water in other processes including the clarification station, as well as, in the filtercake washwater, water movement in the vacuum pan, and washwater in centrifugals is also important.

\(^\text{21}\) Other measures include: (i) Use of highest allowable exhaust steam temperature (< 130°C) (ii) A higher juice temperature can be used in the evaporator station (iii) Use of special evaporators to reduce retention time – e.g. Kestner, falling film, plate (plate/platular for heaters) (iv) Flashing of condensates (5% on evaporation) can be done.

\(^\text{22}\) For every 5°C increase in feed water temperature, an efficiency improvement of 0.5% can be achieved.
monitor and automatically control the operating conditions of the boiler and steam production\textsuperscript{23}.

7) Selection of boilers and auxiliaries
The boiler is the most important system in a cogeneration power plant. Boiler selection requires careful technical evaluation especially regarding achievable boiler efficiency and the power consumption of the boiler auxiliaries.

3.6. Environmental Impacts/benefits
Bagasse is a natural, clean and renewable source of energy. The environmental benefits of bagasse cogeneration are mainly related to low gaseous and particulate emissions.

Bagasse combustion is environment friendly because it produces low particulate, CO\(_2\) and other greenhouse gas emissions. This is particularly true where bagasse cogeneration replaces carbon-intensive fossil fuel generation. Bagasse is free from sulphur and, therefore, does not emit any harmful sulphur dioxide/trioxide gases when burnt in the boiler. Since bagasse combustion can be carried out efficiently at low temperatures, the resultant NO\(_x\) emissions are also less compared to fossil fuel burning.

The air pollution from sugar mill cogeneration units is mainly from particulate matter arising out of fly ash. To meet the allowable limits, dust collectors of efficiency in excess of 94\% are required, and these include electrostatic precipitators (ESP) and bag house filters. Both ESP and bag house filters can be designed to achieve dust collection efficiency of 99.9\%. (See Thematic Report 4 for a more detailed analysis of the environmental impacts and benefits of bioenergy production and use from sugar cane resources).

3.7. Economic Benefits of Bagasse Cogeneration
Bagasse based cogeneration has the following economic benefits:

1) \textbf{Increased viability of sugar mills}
The revenue stream resulting from the sale of surplus power to the grid increases the financial standing of the sugar industry. This is especially true as the sugar-milling season often coincides with peak electricity demand loads. Therefore, sugar mills can thus benefit immensely from the opportunity to sell electricity to the grid. This opportunity is limited in countries that produce low cost electricity from large coal-fired power stations.

2) \textbf{Reduced fuel costs}
The capital costs of bagasse cogeneration plant are among the lowest of all renewable forms of power generation. The cost of electricity from bagasse is comparable to small hydro, but is much lower compared to solar photovoltaic and wind. Bagasse

\textsuperscript{23} The most important technical parameters in the boiler to be monitored include furnace draught, CO\(_2\), steam temperature, fuel flow, steam flow, boiler drum water level, feed water supply and air. These are regulated either by manual operation or by automatic control. For automatic control, either Programmable Logic Controllers (PLCs) or Distributed Control Systems (DCSs) can be adopted.
cogeneration projects have short gestation period, as the technologies used are proven and well established. Where domestic supplies of coal are plentiful and the environmental costs of coal are not considered, then it is more difficult for bagasse cogeneration to compete economically\textsuperscript{24}. However, where the environmental costs of coal are addressed to some extent, such as through legislation or through carbon finance mechanisms, then bagasse cogeneration can be cheaper than coal.

3) **Energy security**

The use of a local fuel source guarantees security of energy supply, reducing the dependency on imported fuels like coal, and therefore, achieve more balanced trade and save foreign exchange. Use of other biomass fuels during off-season enables the cogeneration plants to operate beyond the crushing season for up to 300 to 330 days. Sugar mills that produce and export electricity also increase grid stability and reliability, as well as, decreasing the need for high capital investments that would otherwise be required to upgrade transmission equipment and maintain reliable power supply.

4) **Decentralized generation**

Bagasse cogeneration, being a decentralized mode of generating electricity, reduces transmission and distribution (T&D) losses significantly by supplying electricity near its generation point whilst reducing loading on grid. In most developing countries like India and Brazil, T&D losses are extremely high (over 20\%), due to long distances between power generation and consumption points. The T&D losses in Mauritius are much lower at around 10\%.

The economics of cogeneration depend on the capital cost, mode of implementation, and the cost of electricity generation. Capital costs are dependent on the technology adopted (backpressure or condensing cum extraction), the pressure/temperature level of boilers/turbines, and automation and controls of cogeneration plant. The capital cost of bagasse cogeneration is in the range of US$700 to US$1,500 per kW. The cost of generation of electricity from bagasse cogeneration plants again depends on a number of parameters and is site specific.

3.8. **Benchmarks**

A set of benchmarks has been developed through actual practices of bagasse cogeneration in three parts of the world namely Mauritius, India and Brazil. The surplus electricity that can be exported to the grid under specific operating conditions is as shown in Table 6.

The surplus exportable electricity in Mauritian power plants has been based on a cane fibre content ranging from 13-16\%, bagasse moisture content of 46\%, process steam consumption of 350–450 kg steam/tonne, cane and power consumption of 27-32 kWh/tonne cane. In India, high pressure and temperature configurations in CEST systems have been widely implemented starting in the 1990s, in part through international technical cooperation programmes (USAID, 2002).\textsuperscript{24}

\textsuperscript{24} In South Africa, which has plentiful domestic coal supplies, bagasse is sometimes sold by sugar factories to paper producers, with the price being roughly equivalent to the cost of coal for electricity generation, i.e. the value of bagasse in this case is roughly equivalent to the coal that is replacing it (Purchase, 2007).
### Table 6: Benchmarks for surplus electricity production

<table>
<thead>
<tr>
<th>Country</th>
<th>Power Mode</th>
<th>Operating configuration</th>
<th>Surplus exportable electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mauritius</td>
<td>Continuous</td>
<td>20 bars &amp; 325°C</td>
<td>25 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>31 bars &amp; 440°C</td>
<td>45 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>45 bars &amp; 475°C</td>
<td>53 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>Firm (CEST)</td>
<td>45 bars &amp; 440°C</td>
<td>75 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>Firm (CEST)</td>
<td>82 bars &amp; 525°C</td>
<td>130-140 kWh/tonne cane</td>
</tr>
<tr>
<td>India</td>
<td>CEST</td>
<td>67 bars &amp; 495°C</td>
<td>90-120 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>CEST</td>
<td>87 bars &amp; 515°C</td>
<td>130-140 kWh/tonne cane</td>
</tr>
<tr>
<td>Brazil</td>
<td>Continuous</td>
<td>22 bars &amp; 300°C</td>
<td>0-10 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>42 bars &amp; 440°C</td>
<td>20 kWh/tonne cane</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>67 bars &amp; 480°C</td>
<td>40-60 kWh/tonne cane</td>
</tr>
</tbody>
</table>

*Source: Seebaluck et al., 2007*

For Brazilian conditions, bagasse production averages 280kg/TC, with moisture content of 50%, and with boiler steam condition of 22 bar at 300°C. At these operating conditions, very little surplus power can be produced. In Brazil, the aim of the mills is, therefore, to reach self-sufficiency in energy than to optimise for cogeneration; the price offered by the utility is not sufficient from the private sector perspective to justify investments in factory energy and process efficiency that could, otherwise, facilitate the profitable export of surplus electricity.

### 3.9. Potential for Bagasse Cogeneration in SADC

From the 45 million tonnes of cane crushed each year in the region, potential electricity exports from SADC sugar mills are estimated to be 5.7TWh using high pressure boilers (82 bars) and high temperature technology (525°C). About 50% of this potential can be realised in South Africa. Mauritius, Swaziland and Zimbabwe account for about 33% of the remaining potential in the region. At 45 bar and 440°C, the total potential decreases by about 42% to 3.3TWh, while another 40% reduction in potential is achieved when pressure are reduced to 31 bar. See Annex A for details on potential in each country at different operating conditions.

### 3.10. Opportunities and Best Practices for Cogeneration in SADC Countries

The replication of bagasse based cogeneration energy projects in the African continent could offer huge opportunities for diversification in the sugar industry, as well as, to enhance the market penetration of renewable energy from sugar cane biomass. Electrical energy derived from bagasse is a commercially proven technology, and its exploitation in sugar cane producing countries would allow the reduction or substitution of fossil fuels mainly used for sustaining the energy sector. The key factors that could enhance bagasse cogeneration in SADC region are as follows:
A number of SADC countries have sufficient crushing capacity (i.e. South Africa, Malawi, Swaziland and Zimbabwe). It has been demonstrated in Mauritius that for cogeneration to be cost-effective, the minimum crushing capacity should be around 200-300 TCH.

Rehabilitation of sugar mills, which is currently underway in Tanzania and Mozambique, should be accompanied by modernization and capacity improvement of sugar mills and associated cogeneration plants through replacement of steam powered mill drives with electro-hydraulic or D.C. electric drives.

Diffusion is a well-established technology, especially in South Africa, and is less energy intensive than milling, and presents opportunities for maximising energy for cogeneration.

Mainland southern African countries have longer crushing periods, around 250 days as compared to 180 days for Mauritius, such that the availability of bagasse is extended; there is lesser need to get recourse to a complementary fuel to run the power plant and cogeneration is possible almost all year round.

Bagasse energy systems can be constructed in a modular way such that expansion can be economically done and thus expansion and growth is easier through continuous R&D. Furthermore, bagasse cogeneration systems offer flexibility in scale of operation.

Through cogeneration reduced dependence on petroleum products is achievable; the recurrent crisis faced by power utilities in Malawi, Tanzania and Zimbabwe, followed by unprecedented power rationing, show that electricity from bagasse can contribute significantly especially to load centres around sugar mills.

Power generation is usually undertaken by the national utility as a monopolistic activity, whereas, the issue of renewable energy/bagasse cogeneration is more profitable if undertaken by Independent Power Producers (IPP). Current restructuring and reforms in the regional power sector needs to promote IPPs such as in the sugar industry.

Electricity tariffs offered by the national utilities for the sale of surplus cogenerated electricity to the national grid should be attractive to encourage sugar mills to invest in power production. Conducive national policies should therefore be defined to promote this type of investment involving guarantee of purchasing power supplied by sugar factories on a long term basis (e.g. over 20 years), and paying a reasonable price of generation cost plus a margin with annual escalation of price per unit of power.
4. Sugar Resources

4.1. Alternative Utilisation of Sucrose from Sugar Cane

Various alternative applications can be derived from sucrose. A study in Cuba (Paturau, 1989) identified more than 100 alternative applications and gave a very comprehensive overview of the many options for utilising sucrose. Unfortunately, very few of these applications have been commercialised by mills. A general view of the many options from the different feedstock streams of the cane processing industry is presented in Figure 9.

Figure 9: Different feedstock from sugar cane processing

Source: Paturau, 1989

The main feedstocks, as shown in Figure 9, are sugar, molasses, ethanol and bagasse and their processing to obtain the different co-products can follow chemical or biological routes. Historically, ethanol has been considered a co-product of sugar processing in many countries, but it is fast becoming a major product.

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25 Rao (1997) in the report ‘Industrial utilisation of sugar cane and its co-products’ also elaborates the latest developments of by-products from sugar cane biomass. The main sucrose co-products are sugar, syrup, molasses and ethanol. From sucrose, syrup and molasses the following products can be obtained by biological processing, that is, fermentation: organic acids (citric, gluconic, lactic, malic, others), monosodium glutamate, L-lysine, xanthan and dextran gums, fructo-oligosaccharides (FOS), bioplastics (polylactic polymer, PHB) are obtained. Polyhydroxybutyrate (PHB) is being produced in a pre-commercial scale (50 t/yr) facility located in a sugar/ethanol mill in the State of São Paulo.

26 By chemical processing, acetaldehyde, acetic acid, esters, ethers, ethyl chloride could be obtained from ethanol. Vinegar, acetic acid and esters are also normally produced from ethanol. Yeast and their co-products can become an attractive option for the production of feed and food. Many mills in Brazil recover and dry yeast from the normal bleeding from the fermentation process. During 2002-03 it is estimated that 44,000 tons of dried yeast were marketed (Leimer, 2005). India is the world’s largest
4.1.1. **Sugar production**

**Types of sugars**
A variety of sugars are produced worldwide from cane. Raw sugars are yellow to brown made from clarified juice, boiled down to a crystalline solid with minimal chemical processing. Raw sugars are produced in the processing of sugar juice but only as intermediates to white sugar.

Mill white sugar, also called plantation white is raw sugar whose colour impurities have been bleached with sulphur dioxide. This is the most common form of sugar in sugar cane growing areas, but it is difficult to store or ship because after a few weeks of storage, its impurities promote discoloration and clumping.

White refined sugar is the most common form of sugar in North America and Europe. Refined sugar can be made by dissolving raw sugar and purifying it with various treatments (e.g. carbonisation, phosphatation, sulphotation, ion exchange and activated carbon). White refined sugar is sold as granulated sugar which has been dried to prevent clumping.

**Alternative to sugars**
Health concerns (diabetes and obesity) have given rise to low calorie sweeteners and consumer preferences are increasingly changing sugar consumption patterns. Thus sugar, sweeteners and substitutes are now inextricably linked. Understanding these changes is of vital importance to the industry’s long term survival and the wider implication for ethanol production. Alternative sweeteners are gaining ground because of their lower price and numerous applications. They are regarded by some as the sugar industry’s major threat, while others regard sweeteners as an additional market. Low calorie sweeteners (especially those from corn) are mainly used by diabetic patients and for reducing obesity. The US sweeteners market is the world’s largest and most diverse; while the market in China is rapidly growing.

Demand for sugar of all types has continued to grow because the sugar market has been large enough up till now to absorb the additional supply. A combination of population growth and improved living standards has prevented serious competition so far.
4.1.2. Ethanol production

Brazil is the world’s largest producer of ethanol from sugar cane. In the 2004-05 crushing season, ethanol production from cane juice and molasses reached 15 billion litres.

Brazil has become a model of using bio-ethanol as a transportation fuel in a massive programme initiated in the 1970s due to the oil crisis. Its PROALCOOL programme has seen anhydrous ethanol blend with gasoline increase from 4.5% in 1977 to current level of 25%\(^{29}\). There are two types of fuel ethanol in use in Brazil: anhydrous, which is blended with gasoline; hydrous, used in neat ethanol cars. Figure 10 shows the trends in the production of the two types of ethanol in Brazil since 1970.

![Figure 10: Evolution of Anhydrous and Hydrous ethanol in Brazil.](source: Moreira, 2007)

Since March 2003, the so-called Flexible Fuel Vehicles (FFV), that allow the use of gasoline, neat ethanol, or any blend of these two fuels, have been marketed successfully in Brazil. There are currently seven brands and 59 models of FFV vehicles in the market, with a 70% market share of new cars sold in the country\(^{30}\) (Joseph Jr, 2003). More details on the development of the Brazilian ethanol motor industry are contained in the CARENSA Thematic Report 5. See also Annex B for details on fuel specifications and performance of ethanol vehicles.

India is another major world producer of sugar and ethanol, with an annual alcohol production of around 1300 million litres\(^{31}\). With a view to protect the environment,

\(^{29}\) Prior to 1975, ethanol production in Brazil used final molasses as feedstock (so-called residual ethanol), and ethanol was used mostly in industrial application or blended with gasoline.

\(^{30}\) The FFV fleet is around one million cars (plus 2.2 million neat ethanol cars and 16 million gasoline cars).

\(^{31}\) There are 297 distilleries currently in operation in the country, 120 are annexed distilleries and the remaining 177 are autonomous distilleries. Ethanol is produced from molasses only, out of which around 50% is used for alcohol based chemical industries and the balance used for alcoholic beverages.
the Government of India in October 2003 introduced a scheme to blend 5% anhydrous alcohol, and a follow up phase is planned to increase the blend to 10%. The 10% target has not been met so far due to some barriers. First, due to variations in sugar cane production and consequently molasses production, insufficient alcohol has been produced to meet the 1 billion litres of alcohol for the 10% blend (after meeting the alcohol demand by the chemical and beverage industries). In addition, the distilleries are demanding a higher price for alcohol which reduces the viability of blended gasoline. However, the Government of India is keen to make this scheme a success, even by importing alcohol from other countries.

**Biodiesel**

Besides using fuel ethanol in Otto cycle engines, there have been attempts to use this fuel in diesel cycle engines. Biodiesel is attracting a lot of interest from the Brazilian mills. Oil bearing seeds like peanuts, sunflower, soya could be planted and harvested in the cane field renewal areas (20% of total area) and processed at the mill site to extract and transesterify the oil to produce biodiesel; the mill would supply all utility requirements (steam, electricity, cooling water) and effluent treatment.

However, the characteristics of ethanol make it unsuitable for diesel engines mainly due to its low cetane number (~7), and low lubrication capacity. Field trials took place in the 80’s but were discontinued due to these problems and also low diesel oil prices. Interest in ethanol/diesel blends was rekindled at the end of the 90’s, motivated by the huge surplus of ethanol. An important program was created, co-ordinated by the Inter-ministerial Council of Sugar and Ethanol. Blends from 3-15% ethanol were tested and the 7-8% blend was considered to be most appropriate. However, the programme was abandoned again after opposition from automakers and fuel dealer syndicates, and due to increasing costs of the testing program. Also there were operating problems with modern diesel engine concepts (rotary fuel pumps, electronics injection), and the equilibrium of surplus demand of ethanol for Otto cycle engines. Two mills in the State of São Paulo, the Cantanduva and São Martinho mills, have continued until today to test ethanol/diesel blends in sugar cane transportation truck (7% and 10% anhydrous ethanol, respectively), accumulating more than 10 million kilometres of experience.

**4.2. Technologies for Ethanol Production**

**4.2.1. Type of distilleries**

There are two main types of distilleries for the ethanol production from sugar cane: annexed and autonomous distilleries. Distillery sizes vary considerably from a few thousands litres/day to about millions of litres/day. In the early days of the PROALCOOL Program in Brazil, new distilleries were in the range of 30 to 500 kl/day, but those in the range 120 and 180 kl/day were preferred. Today, new distilleries having capacities from 300 kl/day and 600 kl/day are becoming standard.

**Annexed distillery**

An annexed distillery is built alongside a sugar mill, sharing several common systems such as, boilers and effluent treatment, in a very synergistic process. Besides, this set up provides considerable flexibility to adjust the sugar/ethanol production to suit

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32 Recently, one mill added a new distillery with a capacity of 700 kl/day which will be accomplished in a single distillation column set.
market demands and sugar cane quality variations. The feedstock is a blend of cane juice and molasses (B or C) that results in an excellent broth with respect to nutrients and acceptable level of inhibitors of fermentation. Today, around 85% of the ethanol production in Brazil uses this arrangement.

**Autonomous distillery**

This type of distillery is a facility where all sugar cane is used to produce ethanol. It was widely used at the height of the PROALCOOL Program in Brazil, but later most of the autonomous distilleries were converted to sugar/ethanol plants, to increase production flexibility to follow the ethanol/sugar market fluctuations. An autonomous distillery can also be built to operate with molasses purchased from other sugar factories, as is the case in countries like India.

In the past two decades, most of the sugar cane processing capacity has been accomplished through the expansion of existing mills rather than through installation of new mills. It is estimated that from 1992 to 2002, 94% of the new ethanol production capacity resulted from mill expansion. Table 7 shows the evolution of mill set-up from 1990 to 2002 in Brazil.

### Table 7: Evolution of the sugar cane sector in Brazil

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar mills only</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>Autonomous distilleries</td>
<td>180</td>
<td>104</td>
</tr>
<tr>
<td>Sugar/Ethanol mills</td>
<td>168</td>
<td>199</td>
</tr>
<tr>
<td>Total units</td>
<td>375</td>
<td>318</td>
</tr>
<tr>
<td>Sugar cane milled (10^6 ton)</td>
<td>220</td>
<td>318</td>
</tr>
</tbody>
</table>

*Source: UNICA, 2005*

It can be observed from Table 7 that the number of sugar mills with annexed distilleries increased, and the number of both new sugar mill and autonomous distilleries decreased. Another observation is that the capacity of the plants increased. The joint production of sugar and ethanol account for around 85% of the total production.

Since the mid 90s the sugar in sugar cane is being equally divided between the sugar factory and the ethanol distillery; it fluctuates around the 50:50 ratio from one season to the other.

4.2.2. **Modernization aspects of distilleries**

**Technology options for cogeneration – impacts on distillery energy requirements**

Sugar mills in Brazil are under continuous modernization. Until 1999, the major thrust was to achieve self-sufficiency in the energy for the whole plant; and reduce the impact of increased electricity costs charged by the power utilities. Under the Brazilian conditions, the energy demand of the mills average 12 kWh/TC, 16-18 kWh/TC and 500 kg steam/TC for electric, mechanical and thermal energy, respectively. Bagasse production averages 280 kg/TC, with 50% moisture content. Based on these parameters, boiler steam conditions were set at 22 bar /300°C, to fully
meet the mill’s electric, mechanical and thermal energy demand\textsuperscript{33}. Figure 11 shows the simplified diagram of this scheme.

**Figure 11: Simplified flow diagram of the energy section of a typical mill**

However, with the restructuring of the Brazilian power sector and privatization of the major utilities, the legal framework now allows the operation of IPPs. This has increased the interest of mills to generate and sell excess power, and currently mills are replacing old boilers and installing high pressure boilers and back pressure extraction turbine generators (65 to 82 bar steam pressure). Condensing/extracting turbine generators are still rare since they require extensive improvement in process steam economy.

There are several alternative ways to reduce process steam consumption in ethanol distilleries. Starting with the ethanol dehydration section, Table 8 shows the steam consumption of three alternatives: azeotropic distillation, extraction distillation and molecular sieves.

**Table 8: Ethanol dehydration technologies**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Dehydrating Agent</th>
<th>Steam consumption (kg steam/L ethanol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azeotropic</td>
<td>Cyclohexane</td>
<td>1.7</td>
</tr>
<tr>
<td>Extraction</td>
<td>Monoethyleneglycol</td>
<td>0.7</td>
</tr>
<tr>
<td>Molecular sieves</td>
<td>Zeolite beads</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Source: CTC, 2003*

Molecular sieve is the preferred technology in USA where ethanol is produced from corn distilleries, and energy consumption is an important issue for both economic and energy efficiency.

\textsuperscript{33} The mills used backpressure steam turbines, driving the major equipment (knives, shredders, mills, exhaust fans and feedwater pumps) and the power generator, and exhausting steam at 2.5 bar. Very little surplus power (0–10 kWh/ TC) can therefore be produced.
To reduce energy use in the main distillation process, the existing technology may be subjected to small or drastic changes. The minor changes include increasing the ethanol concentration in the wine; changing the distillation columns design to allow more efficient operation; increasing the number of stages (trays) and reducing the pressure drop per stage, to operate with a lower reflux rate; increasing the steam pressure; as well as using the Flegstil technology. These changes are expected to bring about incremental improvements to reduce steam consumption.

Among the drastic changes, is the use of multistage distillation, pervaporation, membrane technology for ethanol separation, and vapour recompression. To establish a continuous fermentation process, the ethanol concentration within the fermentation vessel must be kept at 8% by weight or lower. Pervaporation can maintain the necessary ethanol concentration in the broth. The advantages of using pervaporation in such a system include the ease of processing the clean, nearly pure ethanol extracted from the fermentation vessel and a significantly higher fermentation capacity, or the reduction in fermentor size and costs. In Brazil, the pervaporation technology has not reached the commercial stage. In India, many distilleries are adopting multi pressure distillation, and steam consumption has consequently come down drastically.

Several of these technologies are already at commercial stage and the choice is mainly an economic decision.

4.2.3. Technology

The technology used in Brazil for cane preparation, juice extraction and juice treatment is similar to that found in the SADC region; it has been extensively described in section 2. The following discussion gives an overview of the technology used in Brazil laying emphasis mainly on the differences when processing is done for the production of ethanol.

Cane reception and preparation

When working with whole cane (hand harvesting) the cleaning process consists of washing with water at the top of the feeding table; the amount of water used is considerable (around 5 m³/TC) and can represent an environmental problem unless a closed circuit is used. The sugar loss by washing is estimated to be less than 1.5%. In the case of chopped cane (mechanical harvesting) washing with water is not used due to the high sugar losses that would result. Dry cleaning with air blowing is being developed in several countries like Brazil, Australia, Cuba, Colombia, Guatemala and Mauritius. However, the use of this technology is still at its infancy. In India, the entire cane is manually harvested, and hence, clean cane is supplied to mills. Washing of cane is not prevalent in Indian sugar mills.

The preparation index should be at least 85% in case of milling and 92% for diffusion to ensure efficient sucrose extraction.

Juice Extraction

The performance of both types of technologies used to extract sucrose from cane, that is, milling and diffusion have small differences with respect to extraction efficiency, juice purity and energy consumption. Milling is more flexible for operation and capacity increase, and is the most common technique used worldwide. Investment and operating costs are similar in both cases.
Diffusion may produce good quality juice making; it is possible to use it directly in the ethanol distillery without further clarification. However, this has yet to be demonstrated.

Milling is the preferred technology for sugar cane juice extraction in Brazil, and is used in about 98% of mills. The popularity of this process among the Brazilian mills is probably due to the flexibility that it presents for capacity expansion at minimum investment costs.

In Brazil, the mill consists of a core of three main rolls: inlet roll, upper roll and outlet roll; normally a fourth roll is added – pressure roll – with the objective to increase the throughput and extraction efficiency. In Australia and South Africa, the mills have five or six rolls and slower rotational speed than the Brazilian units, thus promoting a slightly better extraction. In India, most of the sugar mills are equipped with pressure feeders, underfeed rollers, and Donelly chutes to enhance juice extraction.

The normal practice in Brazil is to send the first expressed juice (from the first mill) to the sugar factory and the mixed juice to the distillery.

In the first phase of the PROALCOOL Program, the main interest of the mills was to increase the processing capacity; very little attention was given to factory efficiency, since very ambitious goals had been set for the program (to achieve production level of 10.6 billion litres/year in 1986). The mill technology imported from South Africa and Australia had to be modified to increase milling capacity of the existing milling tandems (CTC, 2003). Table 9 shows this evolution.

### Table 9: Evolution of mill capacities (TCH)

<table>
<thead>
<tr>
<th>Mill Size</th>
<th>Original</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>54&quot;</td>
<td>130</td>
<td>180</td>
<td>190</td>
<td>210</td>
<td>280</td>
</tr>
<tr>
<td>78&quot;</td>
<td>270</td>
<td>375</td>
<td>400</td>
<td>440</td>
<td>480</td>
</tr>
</tbody>
</table>

*Source: CTC, 2003.*

Since the milling tandem accounts for a significant part of the total investment cost in a sugar/ethanol mill, this improvement helped to decrease sugar cane processing costs. Subsequently, the factory efficiency also became a major item. The evolution of the milling extraction is as shown in Table 10.

### Table 10: Evolution of improvements in mill extraction efficiencies

<table>
<thead>
<tr>
<th>Extraction efficiency (%)</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>91.0-93.0</td>
<td>93.5-95.0</td>
<td>94.5-96.0</td>
<td>97.0-97.5</td>
</tr>
</tbody>
</table>

*Source: CTC, 2003*

The evolution phases in Table 9 and Table 10 involved the following improvements:

- **Phase I**: Better cane preparation, introduction of pressure roll and mixed imbibition.
- **Phase II**: Donnelly chute; automation of cane feeding; hard weld deposit on rolls.
- **Phase III**: Donnelly chute; automation in all mills of the tandem.
- **Phase IV**: Improved mill setting and operation control.
**Juice treatment**

After the extraction process, sugar cane juice contains impurities that impair its processing to sugar or ethanol. The primary treatment aims at the removal of the maximum amount of insoluble impurities such as sand, clay and bagasse fines that are in the range of 0.1 to 1%. The main equipment used includes:

1) **Cush-cush screens**
   This is a set of fixed screens, with openings in the range of 0.5 to 2 mm, positioned just downstream of the mills. The collected material, mainly bagasse fines, is scraped and sent back to the milling tandem between the first and second mill.

2) **Screens**
   There are different types of screens (DSM, plane, rotating, vibrating) with openings around 0.2 to 0.7 mm; the screening efficiency is in the range of 60 to 80%. The collected bagacillo is returned to the milling tandem as its sucrose content is high.

This first stage of physical juice cleaning is followed by a second cleaning phase intended to remove the fine impurities, which could be dissolved or present in the colloidal form or even as insolubles. Flocculating agents are added to coagulate or flocculate the suspended impurities. Milk of lime is added to adjust the pH to avoid sucrose inversion or decomposition. After this chemical treatment, the juice is heated to 105-110°C by means of shell and tube or plate heat exchangers that use process steam or vapour bled from the evaporators. The heated juice is directed to a flashing vessel, to remove the dissolved gases, and then discharged to the clarifiers where the most important part of the juice settling process takes place. The most common equipment used in Brazil is the trayless clarifier designed by the Sugar Research Institute (SRI) that has a retention time of less than 45 minutes. Polymers are added to the juice and the clean juice is tapped from the top of the clarifier and sent to the evaporators to be concentrated to a Brix in the range of 65%. In the annexed distilleries, this concentration process is not necessary since the final broth Brix can be adjusted by blending! The juice and molasses. The impurities that are removed from the clarifier, in the form of mud with a solids concentration of around 10%, are sent for filtration to recover the sugars, and represent from 15 to 20% of the juice that enters to clarifier. Before entering the filters, an amount of bagasse fines (bagacillo) is added to the mud to aid the filtration process. The filtrated juice is returned to the process while the filter waste (called filter mud) is sent to the fields as a fertilizer.

Before it is fed to the distillery, the juice must be cooled to around 30°C. The first step of the cooling process is done using mixed juice in regenerative heat exchangers that brings the clean clarified juice temperature down to about 60°C, and the second step uses cooling water. Cooled and cleaned juice is subsequently sent to the distillery.

The decision on whether to pretreat sugar cane juice prior to distillation is dependent on investment costs versus fermentation efficiency. At the beginning of the PROALCOOL program most mills did not treat the juice sent to the distillery, especially the autonomous units. But with the increasing knowledge of microbiological processes and the demonstrated correlation between juice purity and fermentation yield, pretreatment of the juice prior to fermentation (similar to the same technique used in a sugar factory) is now being adopted (with some adaptation).
There are four possible levels of intensity in the juice treatment processes for ethanol production, which result in the correspondingly different impacts on the investment costs of the system and the main fermentation parameters. These include:

- Physical treatment only is the cheapest system.
- Physical & heat shock and cooling treatment (requires between 3.33 and 7.9 times more investment).
- Complete treatment including physical operations, liming heat shock and sedimentation (requires 6.6 times more investment cost) (Rossell, 1988).

The impact on fermentation parameters such as productivity, fermentation time, alcohol concentration in wine, antifoaming agent consumption, and sulphuric acid consumption improves with increasing number of treatment stages.

The best results are achieved with the multistage treatment. The best treatment sterilizes the must (broth) that results in high fermentation yield, but the increased steam consumption sometimes reduces the benefits of increased yield. A clean juice also improves the operation and maintenance of the centrifuges, and reduces the consumption of antifoaming agent, biocides and antibiotics. See Annex C for more details on the impact of juice treatment using the alternative processes.

### 4.2.4. Biological conversion

**Fermentation**

The raw material for the fermentation process is must or broth, a sugar solution with the concentration adjusted to promote yeast activity. It is normally prepared as a mixture of sugar cane juice and molasses with the solids concentration around 18-20° Brix. Water may eventually be used for Brix adjustment.

There are basically two major categories of fermentation processes: the batch and the continuous process.

**Batch fermentation: Melle-Boinot process**

The most popular fermentation technology used in Brazil is the Melle-Boinot process with yeast recovery by means of wine centrifuging. The recovered yeast is cleaned and sterilized before returning to the fermentation vats. This yeast cleaning involves dilution with water and addition of sulphuric acid to bring the pH down to around 2.5, or lower if infection is present. The water solution of diluted and acidified yeast stays in agitation for 1 to 3 hours before being used again.

The main components of the batch fermentation with cell recycle (Melle Boinot) as used in typical Brazilian ethanol producing plants is shown in Figure 12.

Fermentation takes place in carbon steel tanks, called fermentation vats, with a feeding phase that takes normally from 4 to 10 hours. The sucrose is first hydrolyzed by the yeast and then fermented to ethanol, according to the simplified Gay Lussac reaction:

\[
C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 \text{(glucose)} + C_6H_{12}O_6 \text{(fructose)}
\]

\[
C_6H_{12}O_6 \rightarrow 2 CH_3CH_2OH + 2 CO_2 + 23.5 \text{ kcal}
\]
During fermentation, the release of CO\textsubscript{2} causes an intense agitation in the vat and heating. As fermentation is an exothermic reaction, heat is generated and external cooling is necessary to keep the temperature at optimum levels, around 32-34°C. Besides ethanol and CO\textsubscript{2}, as indicated in the equation above, higher alcohols, glycerol, aldehydes and organic acids are produced in traces and these products decrease the ethanol yield.

Total fermentation time, in Brazil, ranges from 6 to 16 hours, but stays mostly in the range of 8-9 hours, and the final ethanol concentration in the wine varies from 7 to 9%. The main parameters of the batch fermentation process are shown in Table 11.

Continuous fermentation
Continuous fermentation is also used and accounts for around 25% of the ethanol produced in Brazil. Continuous fermentation evolved from the Melle Boinot process; a typical configuration is shown in Figure 13\textsuperscript{34}. Its advantages include lower

\textsuperscript{34} There are other variations of these two processes. The first is known as the COMBAT in which fermentation is performed continuously in a large first vat up to a certain point and then finalized in several smaller vats in a batch process. The second is called BATCOM: the batch fermentation process is done in a series of first vats and then finalized in several continuous process vats located downstream. Fermentation efficiency can reach the 92% level but is difficult to maintain this high value due to infections and process parameters fluctuations. Together with juice extraction, they are by far, the most important sources of sucrose losses in ethanol production from sugar cane.
investment costs and easier automation suitable for facilities producing more than 500,000 litres of ethanol per day that can be operated by one person per shift. Its main disadvantage is the difficulty to handle infections. Continuous fermentation normally uses three to five vats in series, with more than 60% of the sugars being consumed in the first one (See Figure 13). The first large scale fermentation plant (200,000 litres ethanol/day) started operating in Brazil in 1982, in a Copersucar mill (Rossell, 1988). In India, more distilleries have switched over to continuous fermentation as from 1985. The equipment was originally supplied by Vogel-Busch from Austria and Alfa-Laval from Sweden, until local capacity was developed. Around 150 distilleries use continuous fermentation out of the 297 distilleries found in India.

Table 11: Typical parameters of the Melle Boinot fermentation process

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Capacity</th>
<th>Additional Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermentors</td>
<td>8-12</td>
<td>300 m³</td>
<td>Carbon Steel cylindrical fermentors, Conical bottom</td>
</tr>
<tr>
<td>Centrifuges</td>
<td>3-6</td>
<td>45 m³/h</td>
<td>Disc centrifuges, with nozzle discharge</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>4 – 6</td>
<td>1,200,000 kcal/h</td>
<td>Plate type</td>
</tr>
<tr>
<td>Productivity</td>
<td>4 – 7</td>
<td>Ethanol kg/m³/h</td>
<td>Weight of ethanol (kg) per volume of fermentation tanks (m³) per unit of time (h).</td>
</tr>
</tbody>
</table>

Source: Rossell, 1988

The evolution of the fermentation technology in Brazil can be represented by the optimisation of the fermentation time, yield and final ethanol concentration in the wine (See Annex D). Fermentation process in Brazil is now fully mature having reached peak performance in the 1990s. Although there is very little potential for further gains in yield and fermentation time reduction, there are several possible improvements that can further reduce the production costs mainly through steam economy in the distillation plant as discussed earlier in section 4.2.2.
Figure 13: Multistage continuous fermentation process.


The typical process parameters are given in.

Table 12: Typical parameters of the continuous fermentation process

<table>
<thead>
<tr>
<th>Equipment and performance data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First fermentor volume</td>
<td>700 m³</td>
</tr>
<tr>
<td>Number of fermentors</td>
<td>3 – 5</td>
</tr>
<tr>
<td>Number of heat exchangers</td>
<td>3</td>
</tr>
<tr>
<td>Air flow rate in pre-fermentors and first reactor for aeration and stirring</td>
<td>0.01 vvm</td>
</tr>
<tr>
<td>Productivity</td>
<td>4-8 m³/kg of ethanol/h</td>
</tr>
<tr>
<td>Must (broth)</td>
<td>Same as Melle Boinot process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wine:</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total reducing sugars</td>
<td>below 0.5%</td>
</tr>
<tr>
<td>Ethanol content</td>
<td>7-11°GL (8.3°GL on average)</td>
</tr>
<tr>
<td>Yeast concentration</td>
<td>7-12%</td>
</tr>
<tr>
<td>Yeast viability</td>
<td>40-75%</td>
</tr>
<tr>
<td>Fermentation temperature</td>
<td>32-36°C</td>
</tr>
<tr>
<td>Residence time</td>
<td>6-9 h</td>
</tr>
<tr>
<td>Fermentation time</td>
<td>4-7 h</td>
</tr>
</tbody>
</table>

Distillation
This is highest energy consuming phase during ethanol production (in the form of process heat). The wine with an ethanol content around 8% v/v is processed in successive columns, in a sequence of processes: from distillation, rectification to dehydration. Figure 14 shows a simplified flow diagram of the entire process.

Figure 14: Flow diagram for the production of sugar and ethanol
The distillation phase takes place in three stacked columns: A, A1 and D in the flow diagram. Here ethanol is partially extracted from the wine and the residue is collected at the bottom as phlegm (40 to 50°GL), and is directed to column B for further extraction. Some undesirable contaminants are removed in this process such as, aldehydes and esters. The volatile contaminants are concentrated in column D and removed from its top.

Rectification involves concentrating the phlegm to about 96°GL, in columns B1 and B, and the removal of more impurities (higher alcohols, aldehydes, esters, acids, etc.).

The main product of this phase is hydrous ethanol; the effluent or phlegm is recycled or dumped as vinasse or stillage.
Dehydration
Hydrous ethanol, with 96°GL, is an azeotropic mixture of ethanol and water, and therefore cannot be concentrated more by mere distillation. Additional water removal is accomplished by a dehydration process. There are three main dehydration technologies used in Brazil: Azeotropic distillation, extraction distillation with monoethyleneglycol (MEG), and molecular sieves technology.

The choice of ethanol dehydration technologies is based on investment costs, operating costs, energy consumption and application of ethanol (fuel, beverage or industrial). Molecular sieves have the highest initial investment cost while azeotropic distillation has the lowest, and for this reason the latter continues to be the first choice in Brazil. However, molecular sieves have the lowest operating costs and azeotropic distillation has the highest.

In energy economy both molecular sieves and extraction distillation with MEG have similar performance, which is much better than azeotropic distillation. Finally, for ethanol intended for human consumption, the best option is undoubtedly the molecular sieves, since it is a pure physical process with no chemicals coming into contact with the ethanol (as in the case of azeotropic distillation and MEG). Molecular sieves also allow for higher dehydration to be achieved for extra dry ethanol (99.95% purity).

Since 2000, Indian distilleries have adopted ‘Molecular Sieve Technology’ to produce anhydrous alcohol required for a 5% blend with petrol. See Annex F for a review of alternative ethanol production technologies.

4.3. Alternative Feedstock for Ethanol Production

This section assesses the most promising feedstock, with particular reference to southern Africa and Brazil. Ethanol can be obtained from many different feedstocks, in fact from any sugar containing raw material, which can be classified into three main groups:

i) sugars (i.e. sugar cane, molasses, fruits, etc.), that can be converted to ethanol directly via fermentation;

ii) starches (i.e. grains such as maize, root crops such as cassava), which must first be hydrolysed to fermentable sugars; and

iii) cellulose (i.e. woody material, agricultural waste, black liquor from pulp and paper), which must likewise be converted to sugars by the action of mineral acids or enzymes (e.g. acid or enzymatic hydrolysis).

Currently ethanol is produced from a large variety of feedstocks e.g. in the USA nearly 30 different feedstocks are used, either commercially or experimentally, including, cheese whey, beverage industry wastes and potato wastes. New plants using different feedstock include: two barley & wheat, one sugar cane bagasse, two forestry and wood residues, one rice straw, and one Municipal Solid Waste.

However, in reality economic production of ethanol is possible from only a few types of raw materials. Exceptions are sugar cane, maize (corn), wheat, sugar beet, cassava, or sweet sorghum. Currently, sugar cane and corn account for approximately 95% of global bio-ethanol production.
Sugar cane
Sugar cane is the most important feedstock for ethanol production and will remain so in the future, primarily in sugar cane producing countries, due to a number of reasons. First, it is widely produced in over 100 countries. Second, it is the best synthesiser of solar energy into biomass, like sugar and cellulose, and it is also a very efficient crop with very high productivity and potential. Third, there are few real alternatives to sugar cane, primarily in sugar cane producing countries. Sugar cane is already embedded in many cultures, and there is a considerable accumulated experience compared to other crops. Lastly, it is the most efficient crop for conversion to ethanol and has additional benefits (e.g. an ethanol plant using sugar cane can be energy self-sufficient, export surplus energy to the grid and generate many other commercial by-products).

Molasses
Molasses is at the core of ethanol production in many countries and thus needs to be assessed in greater detail, although in Brazil molasses does not play such key role. Molasses can be produced from any sugar containing material.

There are various types of molasses:

i) Integral or unclarified molasses
Integral high-test molasses (IHTM) are produced from un-clarified sugar cane juice which has been partially inverted to prevent crystallization, and has then been concentrated by evaporation to about 80% dry matter (DM) content.

ii) High test molasses
High-test molasses are basically the same as IHTM but the juice has already been clarified before evaporation and thus impurities have been removed.

iii) “A” molasses
“A” molasses is an intermediate product obtained upon centrifuging the “A” massecuite in a raw sugar factory; approximately 77% of the total available raw sugar is extracted at this stage. “A” molasses is produced simultaneously with the “first” or “A” sugar, containing 80-85% of DM.

iv) “B” molasses
“B” molasses (or second molasses) is also an intermediate product obtained from boiling together “seed-sugar” and A molasses to obtain B massecuite, which is centrifuged to extract an additional 12% of the raw sugar. After this about 89% of the total recoverable sugar (TRS) in the processed cane has been extracted; B molasses contains 80-85% of DM and usually does not crystallise spontaneously.

v) “C” molasses
“C” molasses (final or blackstrap molasses), is the end product obtained by the combination of virgin sugar crystals obtained from syrup crystallization and “B” molasses to form a “C” massecuite, which after boiling and centrifuging produces “C” sugar and “C” molasses. “C” molasses is the end of the product although it still
contains about 32-42% of sucrose; this sucrose cannot be fully recovered yet at economical costs\textsuperscript{37}.

There are advantages and disadvantages of using juice, “A”, “B”, or “C” molasses. Much depends on the specific circumstances and market value of both sugar and ethanol. If the aim is to produce mainly sugar, the preferred option is to use “A” and “B” molasses because of their higher sugar content. This is not necessarily the case if ethanol is the major product because it can be produced from lower and poorer quality feedstock such as “B” and “C” molasses\textsuperscript{38}.

The use of cane juice, various types of molasses and mill flexibility (i.e. to produce either sugar or ethanol) need further investigation to ascertain the main technical benefits, the marginal costs of using different types of molasses, the main advantages of using cane juice to produce ethanol, etc. The question is whether other countries should use the same flexible policy of switching to “A”, “B” and “C” molasses or juice. In India, all the 297 distilleries use only “C” molasses for the production of alcohol by fermentation. For southern African countries an alternative could be to switch to “B” molasses or to sweet sorghum to complement “C” molasses. However, any new alternative feedstock involves many changes and will probably be more expensive. Much will depend on the type of distillery.

The technology for producing ethanol from molasses is mature and thus major breakthroughs are unlikely. The key factor may be the introduction of innovative management approaches particularly the use of by-products and waste streams. Another factor that must be considered in more detail are the implications of synthetic derived ethanol from coal and natural gas in South Africa and its wider implications for ethanol production from sugar cane and other crops.

**Sweet Sorghum**

Sweet Sorghum is a good alternative for ethanol production, primarily as a complementary crop with sugar cane, particularly in southern Africa. Its main advantages include a short growing cycle (4 months), resistance to droughts due to its lower water requirements, high propagation (e.g. 4.5 kg/ha of seed compared to 4500-6000 kg/ha of sugar cuttings), potential high productivity (e.g. 7,000 to 8,000 l/ha of ethanol has been reported).

However, a few problems have been reported, including:

i) Difficulties with transport (high biomass content).

ii) Fermentation problems.

iii) Rapid decaying.

\textsuperscript{37} In some countries it is not economic to produce ethanol from “C” molasses e.g., in some South African mills, extraction efficiency is high and thus makes “C” molasses use uneconomical. On the contrary, in Australia ethanol production can only be justified if “C” molasses are used. The cost of a litre of ethanol from “C” molasses was estimated for 2001 at A$0.56 cents and A$0.72cents/l for “B” molasses. Brazil is unique in the sense that it uses “A”, “B” and “C” molasses, and also cane juice directly to produce ethanol, but this has not been always the case. In the first phase of Proalcool (1975-1979), hydrous ethanol was produced from C molasses. It was not until the second phase (1979-1985) when the autonomous distilleries were built that ethanol (hydrous) was produced directly from cane juice.

\textsuperscript{38} Production of ethanol is also preferred on rainy days during the crushing season because of the higher impurities associated (e.g. mud) and when mechanical harvesting is involved (e.g. dust, small stones, etc). This is because production of ethanol is less stringent so far as the quality of the feedstock is concerned.
iv) Small-scale farming, e.g., although 90% of area under sorghum is in developing countries, over 60% of total production takes place in industrial countries; it is produced by many low income farmers mostly for food.

v) Lack of experience with large-scale industrial applications; commercial plantations are mostly in the industrial countries that are unlikely to use it for ethanol production in any meaningful way due to generally unfavourable climatic conditions and high costs.

There have been many attempts to use sweet sorghum as ethanol feedstock, particularly in China, USA, EU, etc. In Brazil various experiments were carried out during the early stages of PROALCOOL but were abandoned because of the difficulties of supplementing sweet sorghum with sugar cane, e.g., rapid decaying, short season which did not coincide with cane; attitudes of sugar cane growers, e.g., lack of experience with sweet sorghum, higher costs, problems with crystallizing sugar, etc.

Other sources of alcohol
As indicated, there are many crops that can be used as feedstock but only a few will meet the economic criteria. Other major possible ethanol production feedstocks include:
- Cassava
- Wheat
- Sugar beet
- Maize (corn) and
- Cellulose.

Annex G provides more details on these alternative crops and feedstock types.

Another potential alternative is synthetic fuels, both from fossil fuels, particularly natural gas and coal, and from biomass. Environmental pressures are driving improvements in the quality of fossil fuels (liquid and solid) and this is expected to continue into the future. Cleaner fuels are becoming a reality and this has major implications for renewable transport fuels such as ethanol39.

4.4. Options for Stillage Disposal and Potential Use

Stillage (or vinasse) is produced from either cane juice and/or molasses fermentation. The use of stillage deserves particular attention due to its potential large impacts. The sugar cane industry in Brazil has made considerable strides in controlling environmental impacts. For example, its main effluents (stillage, filter cake, boiler ashes) are re-cycled and used as fertilizer, and thus this is an area where Brazil can provide considerable know-how. Production processes do not usually have significant environmental impacts (e.g. there are no extreme temperatures, toxic chemicals, and no sulphur in boiler exhaust is produced).

39 For example, one of the most pressing requirements, low or sulphur-free fuels, are already in the market. They are manufactured synthetically via the FT or GTL processes, which are of the same or even better quality, of conventional petrol and diesel. Marketing of FT fuels is anticipated for 2005 when a number of GTL plants will go into operation. FT diesel has been produced by SASOL in South Africa for many years; Shell operates a plant in Malaysia and new plants are planned in the USA. The development of new catalytic processes is cutting costs significantly. For example, GTL technologies have a breakeven point of about $15-20/bbl crude oil if produced in remote areas (Maly & Degan 2001).
4.4.1. Characteristics of stillage

Chemically, vinasse composition varies according to the soil, sugar cane variety, harvesting method, and the industrial process used in the production of ethanol. Its colour, total solid contents, and acidity may vary according to the type of vinasse, processes and treatments.

Vinasse contains unconverted sugars, non-fermented carbohydrates, dead yeast, and a variety of organic compounds. The hazardous substances present in the vinasse generate a very high BOD (Biological Oxygen Demand), ranging from 30,000 to 40,000 mg/l and a low pH of 4-5, because of the organic acids which are corrosive requiring stainless steel or fibre glass to resist it (Freire and Cortez, 2000). The large volume of vinasse and its high BOD and high COD (80,000 to 100,000 mg/l) poses a problem for its disposal.

4.4.2. Disposal Options

Because vinasse is produced in large volumes, one possibility of reducing its polluting effect is recycling it in the fermentation process. Vinasse may be partly used to dilute the sugar cane juice or molasses in the fermentation step. The juice or molasses need to have the Brix adjusted to allow proper yeast growth, a process that normally requires water to dilute it. Alfa Laval developed a process called Biostil that uses vinasse to dilute the molasses prior to the fermentation step.

Research is also being carried out to decrease production of stillage by developing new yeast strains capable of enduring higher alcohol concentrations. Also, other measures such as stillage evaporative cooling could allow significant reduction in the stillage volume and corresponding disposal costs. The best known technologies for vinasse disposal may be grouped according to its source or point of application as follows:

1) Land application of stillage

This is the large scale solution adopted in Brazil by all mills for stillage due to the high value of this effluent as a fertilizer. The application area corresponds roughly to 30% of total cane fields, essentially in the ratoon areas. In the 60s the stillage was dumped in water bodies, but in 1982 a Federal Law prohibited this practice, that led to the use of the so-called “sacrifice area”; an area close to the mill where the stillage was dumped for slow oxidization and evaporation, with doses well above 1000 m³/ha. The problems arising from this new option (nauseating odours, insect proliferation, water table contamination, public complains, etc.) has made it practically non-existent today.

Detailed and extensive studies and field testing have shown that stillage is an excellent fertilizer and improves the physical, chemical and biological properties of the soil; namely, it increases the pH and the capacity of cation exchange, enhances the nutrient availability, improves the soil structure due to the addition of organic matter,

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40 Generally, vinasse has a light brown colour and a low total solid content (from 2 to 4%) when it is obtained from sugar cane juice, and a black reddish colour with 5 to 10% solids content when it is produced from cane molasses. About 10 to 16 litres of vinasse are produced per litre of alcohol produced.
increases the water retention capacity and improves the microorganisms population (Donzelli, 2003). This is known as ‘ferti-irrigation’ in Brazil\textsuperscript{41}.

To avoid environmental problems and the inefficient use of stillage, the application dosage have to be established based on the chemical analysis of the stillage, soil analysis, cane fields productivity and environmental conditions (water table depth, proximity to water bodies, etc). Stillage application methods have evolved from the simple tank truck, which simply spread the stillage by means of a perforate pipe in the back of the tank, to the modern sprinkler systems\textsuperscript{42}.

2) Recycling
Recycling is seen as a solution to avoid high transportation costs of the large volumes of stillage generated. In the beginning of the PROALCOOL program in Brazil, the Biostil process was used in several mills, but the technology had to be abandoned due to difficulties in maintaining continuous operation\textsuperscript{43}. However, Chematur Engineering has recently successfully developed this technology further. The most important point of this technology is the small production of vinasse (25% of the volume from the conventional process) with solids concentration of 30-35\%, by weight, that reduces the costs of field application. Chematur also claims the following advantages of the fermentation process: higher ethanol yields, lower water consumption, easier process control, compact layout and energy saving process.

3) Direct use as animal feed
This method is used around some distilleries in the USA (e.g. Shepherd Oil Distillery at Mermentau, Louisiana) adopting the same practice used with vinasse from spirits distilleries, where high grade-high protein vinasse is obtained. Vinasse obtained from molasses or HTM (high test molasses) fermentation is fed directly to the animals, usually beef cattle. Although good results have been obtained, more studies on nutrition and other effects are still needed. In some countries such as Cuba, animal feed from waste stream is an important industrial by-product.

i) Several other alternative uses of stillage have been subject of research and development, achieving different degrees of success. These include fungus production, construction material development, bio-digestion and direct disposal by incineration\textsuperscript{44}. See Annex H for brief insights into these alternatives.

\textsuperscript{41}Potassium is the main mineral nutrient, followed by calcium, magnesium and nitrogen; the high sulphate content causes odour problems with the fermentation of stillage after application in the field. The pH of around 4 can cause corrosion problems in pipelines, pumps and other stillage handling equipment, but does not cause acidification of the soil (on the contrary) due to secondary chemical reactions.

\textsuperscript{42}Stillage is transported to the spraying areas by pipes (fibreglass reinforced plastics), open channels and trucks and the sprinkler systems use high pressure pumps and self-propelled hose reels. The average maximum economic transportation distances is around 12 km and depends on several factors such as topography, cane field productivity, soil moisture, etc. As a general rule, doses of stillage below 300 m\textsuperscript{3}/ha are considered safe.

\textsuperscript{43}There is one Biostil plant in operation in Australia (CSR Sarina Distillery), one in Colombia and 25 in India. No published data have been found for those plants but apparently they are in normal operation.

\textsuperscript{44}Although all these alternatives are already known, only two methods are currently practiced in Brazil for vinasse disposal in any significant scale, i.e. ferti-irrigation, and biodigestion (although the latter has failed to take-off in any significant scale in Brazil, due to the high investment costs and lack legislation requiring such a treatment). However, in India, about 150 of the 297 working distilleries have installed biodigesters to treat vinasse and produce biogas for use as boiler fuel. Also about 50 distilleries are composting vinasse mixed with filter mud and using it as a fertiliser.
Filter mud

Filter mud is another by-product that has proven to have an economic value as fertilizer, due mainly to its phosphorus and organic matter contents. It is produced at a rate around 35 kg/tc and is used during the cane seed planting operation. The main components of the filter mud are shown on Table 13.

Composting and dewatering is often used to reduce the volume and to improve the mineralization of N. In this process, stillage can be added to the composting process, thus increasing the fertilizer potential of the filter mud and reducing the vinasse disposal costs. In India, sugar factories in the state of Tamil Nadu have plants for production of biogas from filter mud. The biogas is used in the laboratory, canteen, etc. as a fuel.

The wax in the filter mud can be recovered by solvent extraction from the dried mud; around 7 kg of wax/tc can be obtained. Although this alternative has a clear technical potential, in Brazil it has failed to reach commercial stage so far. In India, there used to be two commercial scale wax producing plants, which have since closed.

Table 13: Typical composition of filter mud

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical Range (%w.w., dry matter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre</td>
<td>15 – 30</td>
</tr>
<tr>
<td>Sugar</td>
<td>5 – 15</td>
</tr>
<tr>
<td>Crude protein</td>
<td>5 – 15</td>
</tr>
<tr>
<td>Wax and fats</td>
<td>5 – 14</td>
</tr>
<tr>
<td>Ash</td>
<td>9 – 20</td>
</tr>
<tr>
<td>SiO₂</td>
<td>4 – 10</td>
</tr>
<tr>
<td>CaO</td>
<td>1 – 4</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>1 - 3</td>
</tr>
<tr>
<td>MgO</td>
<td>0.5 - 1</td>
</tr>
</tbody>
</table>

Source: Paturau, 1989

Fertilizer economy improves by the use of stillage in the ratoon and filter mud in plant cane and a typical impact is shown on Table 14.

Table 14: Fertilizer application with and without use of mill effluents

<table>
<thead>
<tr>
<th>Macronutrient</th>
<th>Application Rate (kg/ha)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plant cane</td>
<td>Ratoon</td>
<td>Plant cane</td>
</tr>
<tr>
<td></td>
<td>Case 1</td>
<td>Case 2</td>
<td>Case 1</td>
</tr>
<tr>
<td>Nitrogen-N</td>
<td>30</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>Phosphorus – P₂O₅</td>
<td>120</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Potassium – K₂O</td>
<td>120</td>
<td>80</td>
<td>120</td>
</tr>
</tbody>
</table>

Notes:
Case 1: without stillage or filter mud application
Case 2: with stillage application on ratoon and filter mud in plant cane

Source: SMA, 2004
4.4.3. Biogas production

Vinasse biodigestion has the advantage of on-site disposal while guaranteeing the production of a good fertilizer, together with energy recovery through biogas production. Good heating value, combined with its potential for reducing pollution, merits further investigation of vinasse biodigestion. This is particularly interesting because while the sugar cane industry produces large amount of stillage, it still depends on diesel oil for sugar cane transportation. In Brazil, for example, many distilleries intended to produce biogas. However due to high costs, difficulties with special spare parts for trucks etc., there is hardly any distillery currently producing biogas.

The organic matter content of the stillage qualifies it as a feedstock for biogas production, using the widely used process of biodigestion. Biodigestion is a very complex process involving dozens of types of microorganisms and several intermediate compounds. It can be divided into three phases: polymer hydrolysis (fibres, fats, etc) producing basic compounds (sugars, amino acids, organic acids, etc); acidogenic phase where volatile acids, alcohols, CO$_2$, molecular hydrogen, ammonium are formed; and finally the methanogenic phase where microorganisms converts these compounds in, basically, methane and CO$_2$. The last phase is the slowest process and determines the retention time of the reactor.$^{45}$

For diluted effluents with high COD, such as stillage, the upward anaerobic sludge blanket reactor (UASB) has proved to be the best option. Recently, this technology has been upgraded to what is known as expanded granular sludge bed reactor (EGSB), especially the option of reactor internal circulation (IC). Table 15 shows some typical values of main stillage characteristics before and after the biodigestion.

Table 15: Variation of the main characteristics of stillage due to biodigestion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stillage “in nature”</th>
<th>Biodigested stillage</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>4.0</td>
<td>6.9</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>29 000</td>
<td>9 000</td>
</tr>
<tr>
<td>N total (mg/L)</td>
<td>550</td>
<td>600</td>
</tr>
<tr>
<td>N ammonia (mg/L)</td>
<td>40</td>
<td>220</td>
</tr>
<tr>
<td>P total (mg/L)</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>Sulphate (mg/L)</td>
<td>450</td>
<td>32</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>1 400</td>
<td>1 400</td>
</tr>
</tbody>
</table>

Source: Feire and Cortez, 2000

$^{45}$ Depending on the reactor temperature biodigestion can be classified in three types, namely, Psycrophilic (with temperatures below 20°C), Mesophilic (between 20° and 45°C) and Thermophilic (above 45°C). Thermophilic biodigestion has the advantage of presenting the highest conversion rates and lower retention time, but the microorganisms are more sensitive to process parameter variation, especially temperature. The mesophilic type is a slower process but it is more robust with respect to operating conditions, which makes it the preferred option. Psycrophilic biodigestion is not of interest with stillage.

$^{47}$ Calculation: 70,000 Nm³/day x 1/24 day/hr x 21 Mj/Nm³ = 61,250 MJ/hr;
The following observations can be made:
- The COD is highly reduced (70%) but still remains at a high level, maintaining the polluting potential of stillage.
- The quantity of the main nutrient, potassium, is unchanged, assuring the fertilizer value of biodigested stillage.
- The increase in pH reduces the corrosive characteristic of stillage;
- The reduction of more than 90% of the sulphates is probably the main benefit of the biodigestion process because it eliminates noxious odours and the potential of sulphur migrate to the deeper parts of the soil.

Use of biogas

Biogas from the stillage biodigestion has a chemical composition of approximately 60% methane and 40% CO₂ together with small amounts of H₂S. In this condition, the Lower Heating Value (LHV) is around 20 MJ/Nm³; it can be upgraded by the removal of CO₂ and H₂S.

At the mills, the biogas can be used to generate electricity or to substitute diesel oil as truck fuel. The options for power generation are:
- Burn in the bagasse boiler, as a supplementary fuel, to extend the power generation beyond the crushing season; this option is unlikely to be economically justifiable due to the high production cost of biogas and the low thermal efficiency of the mill steam cycle.
- Use in gas turbine or microturbines: this option is also economically unattractive due to the scale, the gas purification requirements and the need to compress the biogas to the gas turbine (GT) pressure. However, the possibility of employing a combined cycle is very interesting from a thermodynamic point of view.
- Use as fuel in motor-generator groups (compression ignition or spark ignition engines): this is the widely used alternative in biogas producing facilities in Europe due to the power range of the plants. The purification of the gas to remove sulphur compounds, moisture and particulates is necessary; the removal of CO₂ is optional, and may be interesting when gas compression is required.

Considering a distillery that produces 400,000 litres of ethanol per day, with a stillage production of 4.8 million litres per day (COD of 50 kg/L and BOD of 20 kg/L), the estimated biogas production is 70,000 Nm³/day (LHV of 21 MJ/Nm³), corresponding to 17 MW. Burning this biogas in Otto cycle motor-generator, the resulting net power would be approximately 5MW, which corresponds to 25 kWh/tc⁴⁷, a considerable amount of surplus power. Unfortunately, under the Brazilian conditions the surplus power generation with biogas from stillage is not economically viable due to the high investment costs required, and the lack of laws or regulations demanding vinasse treatment.

4.5. Assessment /characterisation of Ethanol Plant Options

4.5.1. State-of-the-art technology and possible new options

The configuration for ethanol plants are basically the same with the first step involving fermentation of the substrate to ethanol and separation of the ethanol from the broth. Most advanced fermentation processes increase the productivity of fermentation.
Advanced application of flocculent yeast is in the tower fermentor. Cane juice or diluted molasses is fed into the bottom of the fermentor and slowly rises up the tower through the flocculent yeast. Ethanol concentration increases as the feed flows up the tower, reaching the desired concentration at the top. Because of high yeast concentration, productivity is much more than that of batch fermentation.

Another method is through the Vacuferm technology in which the fermentation tank is maintained at low pressure (vacuum) to enable the ethanol to evaporate off as it is created. This allows high fermentable sugar and yeast concentrations, because at no point does the ethanol concentration approach inhibiting levels. The serious drawback of the process is the energy required to pump off the carbon dioxide to maintain the required low pressure. It has yet to be demonstrated at an industrial level.

One promising continuous fermentation method is the Biostil, produced by Alfa Laval. It consists of a fermentation tank from which the fermenting feed is continuously drawn. Yeast is centrifugally separated from the beer, which is then introduced into the distillation column. The advantage of the Biostil process is that the fermentor feed can have much higher sugar concentration. Biostil has been demonstrated at industrial levels in Australia, Sweden. This process was used in some distilleries in Brazil at the beginning of PROALCOOL, but it presented stability problems and was discontinued. Vogel-Busch of Austria and its partners in India (Praj Industries) have 150 distilleries who have successfully adopted continuous fermentation and multi-pressure distillation process.

**Investment costs**

The capacity of sugar/ethanol plants has been continuously increasing. The majority of new mills being built are designed with annual crushing capacities in the range of 1.5 to 2.5 million tonnes of cane. Sugar industry specialists consider the optimum size of a mill to be around 2 million tonnes of cane per season, with a crushing capacity 12,000 TC/day\(^{48}\); mills sizes below 1 million tons of cane/year (6,000 TC/day) are not considered economic\(^{49}\). Total costs of a 12,000 TC/day plant are in the range of US$75 million, including ethanol storage facilities.

### 4.5.2. Current overall efficiency

Key technical parameters for evaluating the efficiency of a distillery are the fermentation efficiency (the ratio of actual yield of alcohol to the theoretical yield), distillation efficiency (ratio of actual quantity of alcohol recovered to the alcohol contained in the wash distillate) and steam economy (the entire energy in the form of steam used in a distillery is for distillation alone) (Rao, 2001).

For an autonomous distillery, the industrial efficiency is the Total Reducing Sugars (TRS) equivalent of the ethanol produced divided by the TRS of the milled cane\(^{50}\).

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\(^{48}\) A typical 12,000 TC/day mill is a six mill tandem of the 78”x37” size, two 150 ton steam/hr boilers, a one million litres of ethanol per day distillery and 1000 ton sugar per day – there is spare capacity in both the ethanol distillery and sugar factory – for a sugar mill with an annexed distillery.

\(^{49}\) This takes into consideration both the economies of scale in the industrial plant and the logistics and management of the cane fields (increasing the size will increase the fields operations complexity and cane transportation costs).

\(^{50}\) The TRS represents all sugars in the cane converted to reducing (or inverted) sugars. The TRS equivalent of the final products is calculated using the stoichiometric relation of the conversion reactions equation. The mass of dried yeast produced as a by product must be converted to TRS also; due to its small contribution to the total TRS equivalent it is simply multiplied by a fixed factor,
When different products are produced, as in the case of a sugar factory with an annexed distillery, the industrial efficiency is the ratio of the sum of all products TRS equivalent (sugar, ethanol, yeast, molasses, etc) to the TRS of the milled cane.

**Industrial efficiency (IE)**

In Brazil, there are several procedures to calculate the industrial efficiency (IE), in this report, only the direct method is given for TRS.

\[
IE_{TRS} = 10 \times \frac{TRS_p}{TRS_c}
\]

Where:

- \(IE_{TRS}\) = industrial efficiency in TRS
- \(TRS_p\) = total reducing sugars equivalent of all products (kg/tc)
- \(TRS_c\) = total reducing sugar as a % cane

It is important to point out that the industrial efficiency calculated, as shown above, is a weighted average of the efficiency of all production streams, sugar and ethanol being the most important. Since ethanol production is essentially less efficient than sugar production, due to higher fermentation losses, a mill that has a higher ethanol/sugar production ratio will have lower industrial efficiency. Therefore, it may be interesting to compare the performance under different circumstances. See Table 16 for comparison of some operational parameters.

**Table 16: Average and best values of the main performance parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Best Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction efficiency (%)</td>
<td>96</td>
<td>97.5</td>
</tr>
<tr>
<td>Ethanol in wine (%w/w)</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Fermentation efficiency (%)</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>Distillation efficiency (%)</td>
<td>99.5</td>
<td>99.9</td>
</tr>
<tr>
<td>Industrial efficiency ( % TRS in cane)</td>
<td>85</td>
<td>87</td>
</tr>
</tbody>
</table>

*Source: Fernandes, 2005*

### 4.5.3. Major process and technology changes

Both sugar and ethanol production technologies have reached a very mature stage in Brazil. The processes are well established and technical expertise is available. Thus, there is very little potential for gains in efficiency and productivity in the industry (except in cane production).

There are expectations of a little gain in sugar extraction by the use of advanced extraction system being developed at CTC – hydrodynamic extraction system, based on a patent of the late Maxime Riviere of Reunion. However, the higher gains from this innovative system are expected in terms of lower investment and operating costs, as well as, energy economy rather than in extraction efficiency.

Normally chosen around 1.3 to convert the yeast mass to ethanol equivalent. Mills that sell syrup, molasses and other sugar containing masses must convert these products into TRS equivalent using the Brix, purity and RS content data; the TRS equivalent can then be converted to sugar or ethanol equivalent.
In fermentation, the improvements, albeit small, should come from the use of a cleaner and sterile must (broth) that will reduce infections and, consequently, result in a more stable process, higher yields and less use of antifoaming agents and antibiotics.

Improvements in energy (steam) consumption are expected in distillation, motivated by the interest to generate more surplus electricity and operation of the power generation system on a year round basis. Section 4.2.2 gives a more detailed discussion on steam consumption and improvements.

4.5.4. Resource requirements and optimal plant configuration

**Water**

Water is used in several processes such as cooling systems, imbibition, barometric condensers and equipment and floor cleaning.

Table 17 summarizes the main water uses in the mills.

**Table 17: Water use in Brazilian mills (with annexed distillery)**

<table>
<thead>
<tr>
<th>Process</th>
<th>Use</th>
<th>Average flow (m³/tc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cane washing</td>
<td></td>
<td>5.33</td>
</tr>
<tr>
<td>Milling</td>
<td>imbibition, bearing cooling</td>
<td>0.75</td>
</tr>
<tr>
<td>Juice treatment</td>
<td>lime preparation, filters, sulphiting</td>
<td>0.40</td>
</tr>
<tr>
<td>Evaporation</td>
<td>condensers, molasses dilution, cooling</td>
<td>6.09</td>
</tr>
<tr>
<td>Power generation</td>
<td>boiler make up, Turbo Generator cooling</td>
<td>0.70</td>
</tr>
<tr>
<td>Fermentation</td>
<td>must (broth) and juice cooling</td>
<td>4.0</td>
</tr>
<tr>
<td>Distillery</td>
<td>condenser cooling</td>
<td>4.0</td>
</tr>
<tr>
<td>Other</td>
<td>equipment and floor cleaning</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>21.00</strong></td>
</tr>
</tbody>
</table>

*Source: UNICA, 2005*

Most of these processes use closed loop water system and, therefore, the losses are mostly related to evaporation, spilling, make up. Overall, typical water consumption is about 0.92 m³/tc, from 5.07 m³/tc withdrawal (collection) and discharge of 4.15 m³/tc.

The tendency, due to environmental pressures and water costs, is to reduce water collection to around 1 m³/tc and discharge to zero (zero leakage facility). In India, some sugar mills have developed measures to recycle water and are self-sufficient with the water contained in sugar cane. This implies that no water from outside sources is drawn and no effluent is discharged. Going a step further, a few factories are able to supply drinking water to the local community from the water content of the cane.

**Chemicals**

Several chemicals are used in the mills, mostly in very small quantities, such as lubricants, sulphuric acid, lime, biocides, antibiotics, polymers, sulphur, welding electrodes, antifoaming agents, sodium hydroxide, cyclohexane, etc. The consumption varies widely from one mill to the other and, within the same mill throughout the season, and from one season to the other.

**Labour**

Labour use in mills also varies widely among sugar mills, especially across different regions in Brazil. These differences are a result of varying degrees of automation,
local cost of labour (e.g. N-NE versus C-S regions) and the investment costs in automation. A typical well managed mill in the Center-South region (C-S), milling around 2 million tons of cane per season (12,000 TC /day) has a staff of around 350-400 industrial workers and 150-200 in the administration (total factory and field administration). In Indian sugar mills about 600 people work in a 5,000 TC /day mill.

*Optimal plant configuration*

Several technological advances are important to consider in configuring an ethanol factory. The first is continuous fermentation (through increased yeast concentration), which has become a valued alternative to batch processing. Continuous processing increases the productivity of fermentation, that is, the amount of ethanol fermented per litre volume per hour. High productivity reduces the volume capacity required for fermentation tanks, thereby reducing costs. In distilleries, low steam utilisation technologies have been introduced through heat integration using waste heat in heat exchangers which is then re-used to increase the temperature and/or pressure of other processes. Such approach leaves more steam for electricity generation, thereby improving the economics of production (Cornland et. al, 2001).
5. Other Fibre Co-Products from Sugar Cane

Fibre resources from the sugar cane industry can be classified into field resources and factory resources depending on the location where these resources are generated. Bagasse (a factory resource) is the fibrous residue that is left over after extracting the juice and is the main co-product of sugar cane processing. Bagasse application for power and process heat generation has been discussed earlier in section 3, representing its key traditional commercial functions. The following sections present the scope, opportunities, challenges, and some international experiences of other co-products from fibre resources of sugar cane.

Field-based fibre resources are also known as harvest wastes. These consist of leafy trash (dried leaves of sugar cane) and green tops. In India, Thailand, and Africa where sugar cane is harvested manually or by semi-mechanical or green cane harvesting methods, large quantities of green tops and leafy trash are left over in the fields at the time of harvesting. Such resources are not available in countries where mechanical harvesting is adopted because cane fields are burnt before employing mechanical harvesting.

5.1. Co-products of Field-based Fibre Resources

According to a field study conducted in Brazil (Braunbeck et al., 1999), tops and green leaves comprise 8%, dried leaves (trash) 20%, and clean cane stalks 72% of the sugar cane harvested. The various applications of these resources are as follows:

1) **Green tops as cattle feed**
   Green tops of sugar cane have high fibre content and little protein. Using the green tops as cattle feed is the most common practice adopted in countries (mainly India) where manual harvesting of cane is employed. The Cuban Ministry of Sugar had developed a mechanical process for the production of Dehydrated Sugar Cane Tops (DSCT) as there is a good potential for export. Green tops and leaves can also be mixed with other ingredients such as molasses, filter-cake, or molasses-urea, corn, corn meal, yellow meal, bagasse pith etc. to improve the nutritive value.

2) **Green tops for field applications**
   The cane tops and leaves are generally left in the field after harvesting of cane to prevent weed growth and soil erosion. It also helps in fertilisation and irrigation.

3) **Cane trash for field applications**
   Trash is used mainly in the sugar cane fields as mulch or incorporated into the soil. This can help increase soil organic matter and available N and P. It also enhances soil diversity in terms of microbial and earthworm populations. When used as mulch, it prevents evaporation of moisture from the soil and, thus, helps conservation of soil moisture and also controls the growth of weeds. It also significantly reduces the risk of soil erosion (CTC, 2005).

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51 In some southern African countries e.g. South Africa and Zimbabwe, the cane is burnt before harvesting to rid the fields of snakes and make it safer for manual labourers to work.
4) **Cane trash as boiler fuel**
Cane trash contains valuable cellulose which can be used either as fuel in boilers or as fibrous raw material in the board or paper manufacturing industry. Trash has high calorific value and lower moisture content than bagasse and hence, has excellent fuel properties. Countries like India, Thailand, Jamaica and Hawaii (USA) employ trash balers to compact the trash for use as fuel in the sugar mill boilers. Sugar mills in India have started realizing the benefits of cane trash utilization as boiler fuel, and as a result trash usage as fuel is gradually increasing. However, the low bulk density and high content of potassium reduces the attractiveness of cane trash as a fuel as it increases transportation costs and causes damage to boiler tubes respectively. However, by mixing trash in appropriate quantities (up to 30%) with bagasse and using better construction materials for boiler tubes, can surmount these problems and ensure optimum utilization of the green fuel in sugar mill boilers.

5.2. **Co-products of Factory-based Fibre Resources**
Bagasse is the major factory-based fibre resource in sugar mills. A number of value added co-products can be produced from bagasse due to its excellent chemical and physical properties. Some of the important applications of bagasse are in (i) pulp and paper (ii) market pulp (iii) dissolving pulp (iv) particle boards and fibreboards (v) corrugated boards and boxes (vi) furfural (vii) xylitol (viii) biogas and producer gas and (ix) charcoal and activated carbon.

5.2.1. **Pulp and paper**
Bagasse has been successfully used for the production of different grades of paper all over the world. Paper is usually produced mainly from fibrous materials like bamboo, cotton stalks, rice straw, soft and hard woods. The advantage of using bagasse is that it does not require debarking or chipping as is required with woods. However, depithing has to be carried out when using bagasse, and this process consumes additional water and energy. In India, about 8% of total bagasse production is currently used for paper production.

The Tamil Nadu Newsprint and Papers Ltd (TNPL) in India is regarded as the world’s largest producer of bagasse based paper, with a daily production capacity of 600 tonnes of paper. It is also a leader in technology for the manufacture of newsprint from bagasse. TNPL has the most advanced paper mill in India with unique bagasse procurement, storing, preserving, handling, processing, and pulping system. It produces 180,000 tonnes of paper and newsprint per annum, consuming 800,000 tonnes of bagasse in the process. TNPL adopted the Beloit-SPB process for the manufacture of newsprint using mechanical pulp. The use of bagasse as a raw material helps prevent the denudation of 30,000 acres of forestland a year in India. There are five other bagasse based paper mills also operating in India. Bagasse based paper plants have also been successfully implemented in Argentina, Peru, Brazil, Thailand, South Africa and Iran.

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52 However, technologies for cane trash utilization in board and papermaking are not yet commercialised.
5.2.2. Market pulp

Market pulp is defined as pulp sold on the open market and excludes any pulp used for captive consumption in a paper mill or its associated uses for the manufacture of paper. Market pulp is predominantly used as a major component in the manufacture of paper and paper products (newsprint, writing and printing papers, catalogue papers, tissues, towelling, wrapping, and bag paper etc.). At present, market pulp is predominantly produced from wood (Canada, USA, Sweden, Finland and Norway constitute 85% of the market pulp production from wood). However, commercial-scale plants were established and successfully operated in Mexico, Latin America, Taiwan, and Australia, where it is produced from bagasse.

5.2.3. Particleboards and fibreboards

Particleboards
Using bagasse for the manufacture of particleboards has many advantages. Since bagasse is in the form of particles, it does not need any equipment or machinery for particle preparation. The only operation required is the depithing of bagasse to remove the pith and separate the fibre to be used as raw material for the manufacture of particle boards. After depithing bagasse, the pith can be used as a fuel in boilers and the fibre is sent for further processing. Most bagasse based particleboards plants are located in Latin American countries, such as, Cuba, Argentina, Costa Rice, Puerto Rico, etc. There are several operational bagasse particleboards plants in India and China also.

Fibreboards
Fibreboard is a panel manufactured from any ligno-cellulosic material mainly by interfacing of fibres, consolidated under heat and pressure in a hot press to varying densities. Bagasse is a potential raw material and already there are several commercial plants successfully using bagasse as feedstock.

5.2.4. Corrugated boards and boxes

In the early days, hard wood and straw pulps were used for making corrugated boards. However, in the recent years, several commercial-scale plants based on bagasse pulp have been set up in many countries. In some plants, 100% bagasse is employed successfully. The corrugated board blanks produced are converted into boxes of different sizes through simple mechanical operations.

5.2.5. Furfural

Furfural is an aldehyde derivative of pentosans found along with cellulose in most agricultural commodities. It is also known as furfuraldehyde. A whole range of derivatives can be produced from furfural, such as, furfural alcohol, tetrahydrofurfuryl alcohol, furfural resins, furans, tetrahydrofuran, and pyrols. The process of manufacturing furfural is based on the hydrolysis of pentosans in agricultural residues in the presence of an acidic catalyst, such as sulphuric acid. A plant at Belle Glade in Florida, USA makes use of bagasse from an adjoining sugar mill to produce furfural, whereas most other plants use oat hulls, corncobs, cottonseed hulls, and rice hulls as raw material. The world’s largest furfural plant based on bagasse is found at the Central La Romana sugar mill in Dominican Republic with an annual capacity of 50,000 tonnes of furfural. In India, a few plants have also been established to produce
furfural from bagasse (Southern Agrifurane Industries Ltd., Oswal Agrofurane Ltd.); there is also a large plant in South Africa.

5.2.6. Moulded bagasse products

Bagasse can be admixed with thermosetting synthetic resins (phenol formaldehyde or urea formaldehyde) and can be hot pressed into any desired shape, by the use of an appropriate mould. Some of the articles that can be produced are boxes for packing fragile instruments, kitchen furniture, tiles, trays, window and door frames. The process consists of depithing bagasse, drying the depithed particles and reducing the size of the particles by using hammer mills. The particles are then separated into different sizes to suit the product to be manufactured\(^{53}\).

The technologies for the production of above-mentioned products using bagasse are commercially proven and successfully operating in various countries. However, bagasse application in the manufacture of the following products is still being explored.

1) Dissolving pulp (rayon grade)
Dissolving pulp, which is also known as rayon pulp, is highly purified alpha-cellulose. It is mainly used for making viscose yarn (rayon) for fabrics. It is also used for medicinal tablets, pharmaceuticals, and other cellulose ethers and esters, plastics, explosives, cellophane, photographic films etc. There is no commercial scale plant at present to produce such pulp, based on bagasse. Currently, commercial plants are based on wood. South India Viscose Industries Ltd. in India installed a 0.7 m\(^3\) circulation type pilot digester with liquid pre-heater. Dissolving pulp from bagasse can substitute softwoods that are currently being used as raw material in the plant.

2) Carboxy methyl cellulose (CMC)
CMC is an ether of cellulose and mono chloroacetic acid. Depending on its degree of purity, it is used for a variety of applications such as in oil drilling, ceramic industry (shiny finish), paint industry (thickener or stabilizer) and wood industry (thickener). CMC is normally produced from waste cotton, rags, cotton cuttings, high-grade wood pulp, etc. The Cuban Research Institute for Sugar Cane Derivatives (ICIDCA) has conducted research on the production of CMC from bagasse, with results that suggest potential applications that may be economically attractive (Valdes, 2007).

3) Xylitol
Xylitol is a five-carbon sugar alcohol and is used in diabetic foods as a substitute for sugar. It is also used as a non-sugar sweetener in children chewing vitamins, gums, tablets, jams, puddings, ice creams, etc. The main raw material used for xylitol manufacture is birch wood, but other raw materials such as rice and cottonseed hulls, bagasse, corn stalks, and coconut shells are also used. Pilot projects for xylitol production from bagasse are being implemented in many countries, but no commercial production has been reported in any country. Taiwan Sugar Research Institute has carried out research in this area with a view to improve the techno-economic feasibility of the process.

\(^{53}\) The Taiwan Sugar Research Institute has developed many types of moulded products from bagasse. Biodegradable food trays have been developed using about 76% bagasse pulp, 12% waterproof agent and heat resistant binder, 7% dispersing agent and 5% flocculants. In India, Sitapur Ply Wood Products Ltd., Sitapur, UP, manufactures different types of plywood products based on bagasse like door and window frames.
4) Biogas and producer gas
The production of biogas from cellulosic materials like bagasse – which also contain lignin - is complicated compared to its production from distillery wastes. There is no reported commercial scale plant producing biogas from bagasse. In India, a pilot plant was developed and operated by the National Sugar Institute in Kanpur (in collaboration with Hungary), for the production of biogas and bio fertilizer from bagasse.

5) Activated carbon
Bagasse is pyrolysed at a temperature of 450º C for a period of 20 hours in the absence of atmospheric air. The activated carbon produced is purified by washing it with dilute and hot hydrochloric acid with a retention time of one hour. The Mexican Institute of Steel research has successfully produced charcoal from bagasse using this process.

6) Plastics and other petrochemicals
Research is currently being undertaken on further developing and promoting biodegradable plastics made from sugar and bagasse that breakdown into water and CO₂ within six months.³⁴ It takes 17 kg of bagasse and three kg of sugar to make one kg of biodegradable plastic. Bagasse-based plastics are still uncommon. However, their chemical resistance, quality, and biodegradability are promising despite the higher costs associated with their development. In the near future, environmental requirements may accelerate a wider dissemination of cane plastics. Bagasse could also compete, to some extent, with other petrochemical products such as adhesives, synthetic fibres, herbicides, and insecticides, as well as, substances like ethyl ether, acetic acid, ethyl acetate, and diethyl amines. Again, the main advantage of bagasse in these applications is its biodegradability.

5.3. Remarks
Cost-effective utilization of cane fibre resources for the production of value added products is yet to be commercialised. Large-scale production of fibre based products is being hampered by a variety of reasons such as lack of poor returns on investments, availability of cheaper alternative resources, high technology costs, lower volumes of production, lack of process development for commercial production, and lack of research and product development work.

³⁴ Petroleum based plastics take about one hundred years to degrade.
6. Co-Production Strategies in the Sugar Industry

In today’s competitive market environment, product diversification and efficiency improvements are some of the key strategies used for ensuring continued economic viability. There is great potential to increase the portfolio of products in the sugar cane industry from the traditional focus on raw sugar. Most sugar factories utilize some of the residual streams such as bagasse, molasses and stillage for various uses. The established co-products have been ethanol and electricity.

Due to market dynamics in the sugar industry, sugar factories are increasingly shifting their focus for sucrose utilization, molasses, juice, fibre and other residual streams. The typical sugar mills strategy has been to try and extract as much crystallisable sugar (sucrose) from the cane as is economically possible. Efficiency improvements in the industry have traditionally focused on maximizing sugar cane yield per hectare of agricultural land, and sugar produced per tonne of sugar cane grown. However, changing sugar market prices are reducing the viability of the traditional strategy. Hence, there is a need for developing viable co-product strategies.

A variety of feasible products have emerged and found markets including:
- Sugar/solids streams and various intermediate products.
- Molasses and cane juice which are valued for the fermentable sugars that can be converted into ethanol, as well as, being used as industrial and agricultural inputs.
- Cane residues, namely bagasse and cane trash, which are valued for their fibre content and organic residues, as well as, their use as fuel in cogeneration plants.
- Other useful by-products and co-products such as stillage serving as input for production of fertilizers and methane gas.

Co-product strategies mainly involve making choices for sucrose and fibre utilisation.

6.1. Sucrose Utilisation Strategies

There are basically four primary strategies for utilizing the sucrose resource:

(i) The traditional strategy of only producing sugar
This is not an efficient strategy especially for southern African countries which have in the past been dependent on preferential EU export markets, with guaranteed sugar prices well above world market prices. Under this strategy, there is normally no value addition to C-molasses unlike under alternative strategies.

(ii) Only producing ethanol (autonomous distillery)
When producing ethanol only in an autonomous distillery, there are significant savings in capital investment costs since only juice preparation and extraction facilities are needed rather than a complete sugar factory. However, a study carried out in Zambia (Cornland et al., 2001) concluded that ethanol-only strategies are not viable considering the regional market, sugar prices and ethanol prices. According to

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55 From the perspective of sugar production, it is the resource that is the valued end product, whereas for ethanol production, all fermentable sugars are useful as feedstock. A decision to produce more sugar (sucrose) reduces the available fermentable sugars for ethanol production. The term “sucrose utilisation” has been adopted for simplification.

56 The study assumed that the price of sugar was US$370 per tonne, the ethanol price was US$45 per liter, and the electricity price was US$3.5 per kWh.
the analysis, the feasibility of an autonomous distillery depends upon both the size of
the market and the size of the sugar cane estate. If ethanol production were prioritized
with the intention to satisfy domestic markets for blending, the size of the distillery
has to be sized to just meet the estimated ethanol demand, and the size of the sugar
cane estate also needs to be optimized accordingly. Savings would be made on
investment in additional sugar cane processing capacity. However, the costs of sugar
cane production do not decline with production capacity, due to high fixed costs.
Similarly the investment cost of the distillery itself is not sensitive to scale.

Therefore, such an option is highly unlikely to be cost-effective\(^{57}\). An autonomous
distillery would need to be operated at a reasonable scale and would require a stable
market at this higher level. This is not likely in the near-term, given that no ethanol
market currently exists in the region. Strong policy decisions in favour of exports, the
introduction of 100\% ethanol engines (or FFV’s), or greater regional interest in
neighbouring countries are examples of developments that could move the market
closer to feasibility in the future.

(iii) Producing sugar and ethanol in fixed quantities
Fixed quantity production generally means reserving all the economically extractable
sugars for sugar production and using C molasses or final molasses for ethanol
production. In some cases, B molasses are used. This practice has been widespread
and employed annexed distilleries to make use of the C-molasses stream while
prioritizing sugar production. At Triangle Estates in Zimbabwe, C-molasses were at
some stage imported from neighbouring Hippo Valley Estates and from, as far as,
Zambia to supplement the B-molasses from the sugar mill (Scurlock et al., 1991).

This option remains viable if sugar prices are competitive, sugar markets are active
and ethanol/oil prices are low. Where sugar markets become saturated and prices
decline, and where ethanol markets emerge, then the industry would fail to capitalize
on such opportunities by remaining in a fixed sugar-ethanol strategy.

(iv) Producing sugar and ethanol in flexible proportions
In this scenario, sugar is extracted up to the first or second stages, resulting in the
production of A or B molasses, respectively. These molasses streams will have
fermentable sugars that can still be economically extracted.

The presence of additional fermentable sugars increases the efficiency of ethanol
conversion. Consequently, if ethanol is expected to have a market value close to, or,
greater than that of sugar, then it makes economic sense to prioritize ethanol
production over some sugar production, by using A or B molasses as the ethanol
feedstock.

If market prices are fluctuating over time, a producer can benefit from having the
flexibility to switch among these alternative balances of molasses use. The capital and
operating costs of the additional processing stations for B and C molasses are not
significant compared to the overall production costs. Consequently, the decision as to
whether to emphasize sugar or ethanol production can be made at margin. Much can
be learnt from the Brazilian experience with respect to ethanol production from
alternative feedstock in a sugar cane plant.

\(^{57}\) However, this might change with the increase in oil prices.
6.2. Fibre Utilisation Strategies

The fact that the sugar cane plant provides its own source of energy for sugar production in the form of bagasse has long been a special feature of the sugar industry. In the traditional approach, sugar factories and distilleries cogenerate just enough steam and electricity to meet their on-site needs. Any factory designed and constructed today can harness the on-site bagasse resource to go beyond meeting their own energy requirements, and produce surplus electricity for sale to the national grid or directly to other electricity users.

There are two main options for selling surplus electricity from a sugar factory. The first option can be to sell to local off-grid customers, such as local industries or rural electricity cooperatives, thereby providing electrical services without the costs (both actual and organizational) that accompany grid connections. Sugar factories, which are almost always located in rural areas in proximity to the cane fields, can be excellent resources for electrifying rural areas and small towns. For areas without a guaranteed market and low local demand, an investment in a cogeneration plant with the intention of selling electricity to the neighbouring communities is not viable.

The second option is to sell surplus electricity to established utilities or distributors, as an independent power producer. This requires appropriate national policies that allow IPPs to generate and supply the public network. It has been found that large industrial scale bagasse cogeneration plant can contribute significantly to increase the renewable share of power generation like the case of Mauritius which accumulated a very enriching experience in bagasse cogeneration. State-of-the-art cogeneration plant with boiler pressure of 82 bars are being operated to export around 130-140 kWh of electricity for each tonne of cane harvested. However, in other countries in southern Africa, the national utilities are not offering competitive feed-in tariffs to encourage this option. As an important input in the productive sector, many governments still maintain some form of control of electricity pricing to lower the cost of production. This has generally stifled development of new electricity generation plants in the region despite the opening up of the electricity industry.

6.3. Co-production of Sugar, Ethanol and Electricity

The traditional focus in the sugar industry has been the production of sugar, but the changing market prices, market saturation and adverse weather patterns have reduced the industry’s viability. There have been a few attempts by the sugar companies to consider all sugar cane resources as a bundle of potential products and services whose value could be maximized together. Co-production strategies present attractive options as they offer flexibility in producing varied quantities of sugar, ethanol and electricity depending on prevailing market conditions.

The decision for or against co-production should be based on the relative economic value of sugar versus ethanol, along with the size of the two product markets. Where ethanol is highly valued and a sufficiently high volume appears likely, then an autonomous distillery would be favoured. Where sugar is highly valued and the market for ethanol is somewhat uncertain, then co-production would be favoured.

As discussed above, there are different economic strategies for co-producing sugar and ethanol, the main choice being whether to produce in fixed or flexible quantities. Autonomous distillery and annexed distilleries share the same design, based on Brazilian standards but differ in scale (the annexed distillery being considerably
Another minor difference arises in the feedstock preparation at the sugar factory which is based on cane juice rather than on molasses.

Co-producing sugar, ethanol and electricity can be accomplished by co-locating (annexing) the distillery and power station with the sugar factory. Molasses, or a mixture of cane juice and molasses, is used as the primary feedstock. The value of molasses from a sugar factory is generally much greater as an ethanol feedstock on-site rather than exporting it to a separate distillery. A distillery not annexed to a sugar factory must obtain feedstock from other sources thereby incurring transportation costs and transaction costs. In addition the ethanol distillery often supplies fertilizer for the cane fields. The power station also annexed to the sugar factory can use the bagasse efficiently to not only satisfy the needs of the factory but that of the distillery as well.

Typical Condensing Extraction Steam Turbine (CEST) operating at 40 to 82 bars can produce enough steam to supply a typical sugar factory and distillery and export 30 to 140 KWh of electricity per tonne cane. CEST systems represent state-of-the-art technology for bagasse cogeneration that is fully commercialized in the marketplace.

Gasification of bagasse for use in a high-efficiency gas turbine is a more advanced approach to bagasse cogeneration but is still at the research and development stage. Two configurations have been extensively analysed and undergone experimentation; the Biomass Integrated Gasifier-Combined Cycle (BIG-CC) and Biomass Integrated Gasifier/Steam Injected Gas Turbine (BIG/STIG). BIG-CC and BIG/STIG can produce twice as much power per tonne cane as CEST systems, however these systems are not commercially mature at present and require significantly higher capital costs.

When a distillery is attached to a mill, the energy requirements in the form of steam and electric power of the distillery are met by the attached sugar mill during the crushing period. Exhaust steam is mostly required for distillation. Due to this practice, by and large, the distilleries have not made efforts to introduce any energy conservation measures to reduce the consumption of either steam or electric power. On the other hand, the autonomous distilleries have their own boilers for generating steam required for distillation and some have power generators for generating electric power. Hence distilleries have to use fossil fuels which significantly affect the energy balance of fuel-ethanol production. In order to reduce fuel consumption, the distilleries have in the recent years introduced many energy conservation measures, including modification of distillation columns designs to reduce steam consumption, and waste heat recovery units redesigned to recover maximum heat.

The combination of sugar-ethanol and electricity can result in significant improvements in economic viability of sugar enterprises. Cornland, et al. (2001) argued that the diversion from sugar into ethanol through flexible production can in effect be “cross-subsidized” through advanced cogeneration systems. For instance, internal electricity demand is lower when sugar production is lower, since sugar production is energy-intensive in comparison to ethanol production. Hence, more electricity can be sold when less sugar is produced. But the effect may not be sufficient to outweigh the disadvantages of the sugar-ethanol price differentials under a high sugar/low ethanol price scenario.

Many sugar producing countries around the world are now planning to increase ethanol production for fuel use. These countries could benefit from lessons learnt in
Brazil about how the sector evolved to present status, where sugar and ethanol share the sugar cane in an approximate 50:50 ratio, with an annual production of around 15 billion litre ethanol. There are a number of institutional and market difficulties which must be addressed before any co-production can be implemented on large scale.

6.4. Range of End Products from Sugar Cane

Jiangmen sugar complex in China is a remarkable and outstanding global example of an integrated sugar cane resource based facility that has proven on a commercial scale the versatility of sugar cane as a resource over a wide range of products and technologies. This complex has also demonstrated the utility of residual streams from traditional cane processing, by conversion into valuable products and applying suitable technologies.

The complex houses 20 different industries which produce 28 sugar cane based products including the following:
1) Based on cane juice: White sugar, refined sugar, raw sugar, sugar with molasses.
2) Based on bagasse: Bleached pulp, glazed paper, typographic paper, offset printing paper, corrugating base stock, copper printing paper, wrapping paper, fibre boards, furfural, binding agents, electric power.
3) Based on molasses: Ethyl alcohol, edible yeast, liquid carbon dioxide, dry ice, fuel oil.
4) Based on yeast: Ribonucleic acid, nucleotide, adenosine triphosphate, cytidine triphosphate, polyinosinate/polycytidylate.
5) Based on press mud: Portland cement, cinder blocks.
6) Based on steam: Condensate water for drug manufacture.
7. Summary and Conclusions

7.1. Overview of Objectives and Main Findings

The main objectives of the study were to analyse the technological characteristics and performance of the sugar industry in southern Africa, and compare them with international best practice, with particular emphasis on resource extraction efficiency and energy economy. In addition, the study examined key technology issues related to juice-fibre separation, bagasse cogeneration and ethanol production options with the intention of developing performance benchmarks for optimal cost-effective cogeneration and distillery configurations and to identify alternative fibre-based co-products utilisation options and other uses of the sugar resource stream.

Key findings of this study are briefly summarised below.

Both milling and diffusion techniques are used in southern Africa for juice extraction, but diffusers constitute about 80% of all installed capacity in the region. There are small differences between the two technologies with respect to extraction efficiency and juice purity. Milling is more flexible for operation and allows capacity increase at minimum costs, but investment and operating costs are similar to diffusion. A properly designed, maintained and operated mill can achieve an extraction efficiency of 98% or above, especially with compound imbibition. Generally, diffusion is less energy intensive than milling and demands about 20% less power than a 6 mill tandem. Although diffusion uses more process steam than milling, it only requires low pressure steam (2.5 bar), enabling more of the high pressure steam to be used for electricity generation. Thus diffusion presents opportunities for maximising energy for cogeneration.

Overall performance in the sugar industry is defined by industrial efficiency index. This is important in setting the benchmarks for the industry. A number of specific performance indicators for sugar mill operation can also be distinguished. Sugar recovery is the key parameter indicating the amount of sugar recovered as a percent of sugar entering the mill. These operating parameters vary within the SADC region as well as across other world regions due to differences in sugar cane quality and varieties, mill equipment age and efficiency, and other specific operating mill conditions.

Milling performance in the region is very high in terms of extraction compared to other parts of the world. In Mauritius, the average cane preparation index is 88, an average mill extraction of 97.2% while 0.6% sucrose loss in bagasse can be achieved. Southern African countries also have high cane preparation index, with 91.7 for Zimbabwe and 91.1 for Swaziland. Mill extraction is high with 97.6 for South Africa and 96.9 for Zimbabwe. The crushing capacity is also very high at 313 TCH in Swaziland and 455 TCH in Zimbabwe. This is comparable to some of leading sugar processing countries such as India and Brazil. Mill extraction in India is 96.0% and in Brazil 96.5%, while the sucrose loss in bagasse is around 0.75%.

Apart from development of technology for new sugar resource co-products, opportunities for improved sugar processing technology are limited, as raw sugar production is a mature and well established process in southern Africa. Prospects still exist though, for process innovation and optimisation, especially related to improved
productivity. Most SADC countries face financial constraints to invest in novel technologies, but opportunities exist for process optimisation and improved productivity through efficient use of resources, including energy, and equipment design. A number of technologies are especially relevant for promoting bioenergy development. Energy conservation techniques allow more steam to be available for electricity generation while saved electricity can be exported to the public grid for sale.

In milling, two-roller milling units have been the emerging technique and their main benefit is low power consumption. The use of electrically driven hydrostatic drives simplifies mill operations, allows easier mill maintenance and has become common where cogeneration is practiced. For clarification, rotary vacuum filters for underflow treatment is the preferred technology in raw sugar factories. In evaporation, five effects evaporation has proven to be the most efficient from Mauritian experience. The most promising technology for steam savings in the evaporator station is the use of long-tube, falling-film evaporators. In an efficient factory, the evaporator station acts as a boiler to supply low pressure steam, while the main boiler is used for supplying high pressure steam for generation of electricity. With regards to crystallization, continuous vacuum pans offer advantages over batch pans both in the stability of steam demand and overall steam requirement. In centrifugation, batch centrifugals have become much larger and more energy efficient although continuous centrifugals are being developed for high-grade sugar but they still have reliability problems.

Improvement in steam economy is possible through improvement of the calorific value of bagasse, energy conservation measures in the milling department, boiling house and boiler house, optimisation of boiler draft system, usage of instrumentation and control systems and proper selection of boilers and auxiliaries. This enables surplus electricity to be generated. Simple energy conservation measures include replacement of turbo drives used for cane preparation and milling with hydraulic or electric drives; reduction of process steam consumption to 42-45% by modifying the juice heating and evaporation system; increasing the efficiency of boiler operations to a minimum of 70%; introduction of more controls in power plant operations; and use of bagasse driers.

The amount of surplus electricity that can be generated from the sugar industry is highly dependent on the fibre content of the raw material, the efficiency of steam generation and conversion to electrical power, and on the efficiency of energy use in the sugar manufacturing processes. Improved technology, can further enhance the bagasse energy potential, but this comes with added capital costs. Bagasse is the primary fibre resource for energy generation. The amount of bagasse generated and its calorific value are key determinants of the potential energy generated. The quantity of bagasse obtained from cane processing varies from 22 to 36% of cane and is affected mainly by the cane fibre content and the cleanliness of cane supplied. The moisture content of bagasse is the most significant parameter that determines its calorific value, usually 45% moisture indicates good milling efficiency.

From the 45 million tonnes of cane crushed each year in the region, potential electricity exports from SADC sugar mills are estimated to be 5.7TWh using high pressure boilers (82 bars) and high temperature technology (525°C). About 50% of this potential can be realised in South Africa. Mauritius, Swaziland and Zimbabwe account for about 33% of the remaining potential in the region. At 45 bar and 440°C,
the total potential decreases by about 42% while another 40% reduction in potential is achieved when pressure is reduced to 31 bar. Thus opportunities for cogeneration are abundant, provided that proper infrastructure and policy measures are in place to promote cogeneration in sugar mills.

Various cogeneration technologies have been identified, namely back-pressure steam turbines, condensing and extraction steam turbines, and the condensing dual fuel system. Condensing extraction steam turbines are the current commercial state-of-the-art cogeneration technology widely used in Mauritius and India. CEST technology generates more electricity per unit input of fuel, although the high unit operating cost of the technology at small scales is a drawback.

Except for Mauritius, most SADC countries have no extensive bagasse cogeneration programmes. Most sugar factories in the region concentrate upon generation of electricity for their own captive consumption to either supplement or replace supplies from the grid. The efficiency of electricity generation in these mills is poor due to the rudimentary technologies that operate with low steam pressure and temperature. Moreover the abundance of cheaper fossil alternatives, such as, coal thermals and hydro, hampers the development of cogeneration on a large scale for electricity export and weighs down national interest in investing in such ventures. A number of pilot projects have nevertheless been initiated with limited success. Only South Africa, Swaziland and Zimbabwe have significant cogeneration project underway. Studies show that cogeneration technology development is successful in Mauritius, India and Brazil because local expertise for design, manufacture, construction, operation and maintenance of cogeneration power plants is available.

Benchmarks for cogeneration have been set through actual best practices in Mauritius and India. Firm power plants can operate at pressures up to 82 bar and temperature 475°C, while continuous power plants use lower pressures and temperatures, within the range of 20-45 bar and temperatures 325-475°C. The excess electricity generated for sale to the national grid varies between 30-140 kWh per tonne of cane depending on the power plant configuration.

The replication of bagasse based cogeneration energy projects in southern Africa offers huge opportunities for diversification in the sugar industry, as well as, to enhance the market penetration of renewable energy from sugar cane biomass. However, some key factors for success have to be taken into account. First, it has been demonstrated in Mauritius that for cogeneration to be cost-effective, the minimum crushing capacity should be around 200-300 TCH. Second, cogeneration is more profitable if undertaken by IPPs. Current restructuring and reforms in the regional power sector needs to promote IPPs, such as in the sugar industry. Third, electricity tariffs offered for the sale of surplus cogenerated electricity to the national grid should be attractive to encourage sugar mills to invest in power production.

Apart from fibre resources, a number of co-products can also be derived from sucrose, syrup and molasses. Sugar has been the traditional commercial product but ethanol is now emerging as an equally important commodity. A whole range of industrial chemicals can also be produced from sugar resources including organic acids, bioplastics, acetaldehyde, acetic acid, esters, ethers, etc. For ethanol production, distillery configurations can be either autonomous or annexed. Annexed distilleries have considerable flexibility to adjust the sugar/ethanol production to suit market demands and sugar cane quality variations, at the same time obtaining steam from the adjoining power plant or boiler station.
The ethanol production technology in Brazil has reached a very mature stage in the industrial sector, in the sense that new gains in efficiency and productivity, as well as, cost reductions will be difficult to achieve. Those countries interested in starting an ethanol production in large scale should look at the lessons learned in the Brazilian programme.

There are basically two major categories of fermentation processes, the batch and continuous process. The most popular fermentation technology used in Brazil is the Melle-Boinot process with yeast recovery by means of wine centrifuging. Continuous fermentation is also used and accounts for around 25% of the ethanol produced in Brazil. Continuous fermentation evolved from the Melle Boinot process. Its advantages include lower investment costs and easier automation suitable for facilities producing more than 500,000 litres of ethanol per day that can be operated by one person per shift. Its main disadvantage is the difficulty to handle infections. There are other variations of these two processes.

A few options are available to modernize distilleries. These include reduction of process steam consumption for ethanol dehydration through use of azeotropic distillation, extraction distillation and molecular sieves. Molecular sieve is the preferred technology in terms of energy economy. To reduce energy use in the main distillation process, the use of multistage distillation, pervaporation, membrane technology for ethanol separation and vapour recompression can be implemented. Several of these technologies are already at commercial stage and the choice is mainly economic.

With the increasing knowledge of microbiological processes and the demonstrated correlation between juice purity and fermentation yield, pre-treatment of the juice prior to fermentation is now being adopted. The best results are achieved with the multistage complete treatment but investment costs have to be balanced with fermentation efficiency.

Ethanol can be obtained from any sugar-containing material, including sugars, starches and cellulose. In reality, economic production of ethanol is possible from only a few types of raw materials, including sugar cane, maize, wheat, sugar beet, cassava, or sweet sorghum. Other feedstocks for ethanol could be feasible but need to be better evaluated for the specific country conditions.

Apart from bagasse, other fibre resources include field-based resources or harvest wastes and factory resources. Field resources consist of leafy trash (dried leaves of sugar cane) and green tops which can be used as cattle feed, application to prevent weed growth and soil erosion, as mulch or incorporated into the soil, or as boiler fuel. A number of value added co-products can be produced from bagasse due to its excellent chemical and physical properties. Some of the important applications of bagasse are in pulp and paper, market pulp, dissolving pulp, particle boards and fibreboards, corrugated boards and boxes, furfural, xylitol, biogas and producer gas, and charcoal and activated carbon.

Waste streams such as stillage have potential large environmental impacts due its large volumes, high BOD and high COD. Vinasse disposal techniques include land application as fertilizer, recycling, biodigestion and direct use as animal feed. Filter mud is another by-product that has proven to have an economic value as fertilizer.
Co-producing sugar, ethanol and electricity can result in significant improvements in economic viability of sugar enterprises. Co-production decisions should be based on the relative economic value of sugar versus ethanol, along with the size of the two product markets. Where ethanol is highly valued and a sufficiently high volume appears likely, then an autonomous distillery would be favoured. Where sugar is highly valued and the market for ethanol is somewhat uncertain, then co-production would be favoured. Research shows the diversion from sugar into ethanol through flexible production can in effect be “cross-subsidized” through advanced cogeneration systems.

7.2. Limitations of the Study
The scope of this study was limited in a few aspects. The approach used to conduct the study was based to some extent on the findings reported by key stakeholders of the sugar industry during workshops, meetings and industry surveys. Accessibility to relevant data pertaining to the technical features of the industry proved to be difficult for certain regions. Some factories were reluctant to provide data especially on the technology and equipment used.

More research needs to be done to study the implications of synthetic derived ethanol from coal and natural gas in South Africa, and its wider implications for ethanol production from sugar cane and other crops. This study also assumed that there is a ready market for electricity; for instance, bagasse based electricity might have to compete with cheaper electricity from hydro in countries such as, Zambia, and cheap coal based power in South Africa.

7.3. Lessons Derived and Recommendations
Product diversification in the sugar industry is fast emerging as key to the sector’s economic viability. Given proper policy framework, several countries have harnessed and exploited the full advantage of sugar cane resources through mainly ethanol and electricity generation. There is great potential to increase the portfolio of products in the sugar cane industry from the traditional focus on raw sugar. The synergies that exist within the product range of sugar resource streams are important in maximizing the benefits of this resource. For instance, research has shown that ethanol only strategies can only succeed given proper market conditions, threshold market prices and national policies. Where these conditions do not exist, such as in southern Africa, it is important to optimize the product range. A lot can be learnt from the success stories of Brazil, India and Mauritius.

There are many advantages to developing renewable energy from sugar cane resources. Apart from economic benefits, there are also environmental and social benefits. For instance, an efficient cogeneration system results in the low fly ash, sulphur, GHG emissions. Construction period for such plants is shorter, they require smaller capital investment, lower running costs, enjoy quicker returns on investment compared to an equivalent fossil fuel based power plant. The rural location of sugar mills enables cogenerated power to be directly fed to local sub-stations, consequently minimizing transmission and distribution losses, and the provision of long feeder lines. The generation of surplus power in sugar factories is ideally suited for rural electrification, and for energizing irrigation pumps and agro-based businesses in the villages.

Production of electricity from bagasse in cogeneration systems and fuel ethanol production are two attractive and well established energy supply sources which can
improve the profitability and competitiveness of the sugar industry. These systems have already been successfully demonstrated and implemented in a number of cane producing countries and the challenge is now for other sugar cane producing countries to replicate, expand or adapt similar systems. A wealth of experience exists in those countries that have successfully developed these systems. The possibilities, as well as, the challenges of large scale production and creating markets for these products can be learnt from the experience of countries where these products are currently being commercially exploited. The potential of these resources for southern Africa is significant with regard to the current state-of-the-art technologies that can be adopted. Additional potential exists by further optimising of the system performance, or by the use of emerging technologies.

The technology for producing ethanol from molasses is mature and thus major breakthroughs are unlikely. The key factor may be the introduction of innovative management approaches, particularly the use of by-products and waste streams.

Experiences from other countries show that energy economy is important in achieving surplus electricity generation, and this requires rationalisation of the sugar mill and/or ethanol distillery operations. Several technological advances are important to consider in optimising ethanol factories. In this regard, continuous fermentation has become a valued alternative to batch processing. It increases the productivity of fermentation, and thereby, reduces the capacity of fermentation tanks, reducing overall costs. In distilleries, low steam utilisation technologies have been introduced through heat integration using waste heat in heat exchangers, which is then re-used to increase the temperature and/or pressure of other processes. Such approach leaves more steam for electricity generation, thereby improving the economics of production.

The use of cane juice, various types of molasses and mill flexibility (i.e. to produce either sugar or ethanol) need further investigation to ascertain the main technical benefits, the marginal costs of using different types of molasses, the main advantages of using cane juice to produce ethanol, etc. The question is whether other countries should use the same flexible policy of switching to “A”, “B” and “C” molasses or juice. In India, all the 297 distilleries use only “C” molasses for the production of alcohol by fermentation. For southern African countries an alternative could be to switch to “B” molasses or to sweet sorghum to complement “C” molasses. However, any new alternative feedstock involves many changes and will probably be more expensive. Much will depend on the type of distillery.

Besides production of electricity and ethanol, other marketable by-products, such as, pulp and paper, industrial chemicals etc., can be produced in annexed plants to the sugar cane processing complex, which has been proved to be successful in a number of industries. Generally, the establishment of such centralised sugar cane processing complex creates further opportunities, and at the same time increases the viability for exploiting additional cane based co-products. Furthermore, from experience of other countries, any increase in sugar cane processing capacity is easier to implement through the expansion of existing mills rather than through installation of new mills. Any new plants should also consider economies of scale effects to operational viability. Sugar industry specialists consider the optimum size of a mill to be around two million tonnes of cane per season with a crushing capacity 12,000 TC/day; mill sizes below one million tons of cane/year (6,000 TC/day) are not considered economical.
References

38. UNICA 2005, Sugar cane energy. Twelve studies the sugar cane agroindustry in Brazil and its sustainability, coordinated by Macedo, I.C., São Paulo, Brazil,2005
ANNEXES
Annex A: Potential electricity exports from sugar mills in the SADC region

The potential for bagasse cogeneration in SADC countries at different power plant configuration is as shown in Table A 1.

Table A 1: Electricity Export Potential from Bagasse Energy in SADC countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Total TC crushed annually $x 10^6$</th>
<th>Power @ 20 bar 325°C (GWh)</th>
<th>Power @ 31 bar &amp; 440°C (GWh)</th>
<th>Power @ 45 bar &amp; 440°C (GWh)</th>
<th>Power @ 82 bar &amp; 525°C (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angola</td>
<td>0.360</td>
<td>9.0</td>
<td>16.2</td>
<td>27.0</td>
<td>46.8</td>
</tr>
<tr>
<td>DR Congo</td>
<td>1.669</td>
<td>41.7</td>
<td>75.1</td>
<td>125.2</td>
<td>217.0</td>
</tr>
<tr>
<td>Malawi</td>
<td>1.796</td>
<td>44.9</td>
<td>80.8</td>
<td>134.7</td>
<td>233.5</td>
</tr>
<tr>
<td>Mauritius</td>
<td>5.800</td>
<td>145.0</td>
<td>261.0</td>
<td>435.0</td>
<td>754.0</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0.397</td>
<td>9.9</td>
<td>17.9</td>
<td>29.8</td>
<td>51.6</td>
</tr>
<tr>
<td>South Africa</td>
<td>22.103</td>
<td>552.6</td>
<td>994.6</td>
<td>1657.7</td>
<td>2873.4</td>
</tr>
<tr>
<td>Swaziland</td>
<td>4.103</td>
<td>102.6</td>
<td>184.6</td>
<td>307.7</td>
<td>533.4</td>
</tr>
<tr>
<td>Tanzania</td>
<td>1.289</td>
<td>32.2</td>
<td>58.0</td>
<td>96.7</td>
<td>167.6</td>
</tr>
<tr>
<td>Zambia</td>
<td>1.600</td>
<td>40.0</td>
<td>72.0</td>
<td>120.0</td>
<td>208.0</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>4.535</td>
<td>113.4</td>
<td>204.1</td>
<td>340.1</td>
<td>589.6</td>
</tr>
<tr>
<td>Total/Avg.</td>
<td>43.652</td>
<td>1091</td>
<td>1964</td>
<td>3274</td>
<td>5675</td>
</tr>
</tbody>
</table>

Source: Deepchand (2000)

A more detailed summary of the different sugar factories in some of the SADC countries where the potential of bagasse cogeneration can be addressed is as shown in Table A 2.
Table A 2: Electricity Export Potential from Bagasse Energy in SADC Countries

<table>
<thead>
<tr>
<th>Factory</th>
<th>Total TC crushed annually x 10^6</th>
<th>TCH</th>
<th>Fibre % cane</th>
<th>Pol % bagasse</th>
<th>Moist % bagasse</th>
<th>Bagasse % cane</th>
<th>GCV Bagasse MJ/Kg</th>
<th>NCV Bagasse MJ/Kg</th>
<th>Power @ 20 bar 325°C (GWh)</th>
<th>Power @ 31 bar &amp; 440°C (GWh)</th>
<th>Power @ 45 bar &amp; 440°C (GWh)</th>
<th>Power @ 82 bar &amp; 525°C (GWh)</th>
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Source: Deepchand (2000)

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<tr>
<td>KG</td>
<td>Msolwa</td>
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</table>

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Annex B: Ethanol fuel specifications and performance of ethanol vehicles

Electronic sensors in FFV’s, measures the composition of the blend and adjust the fuel injection and spark systems automatically without any interference from the driver. According to the Brazilian automakers (Joseph Jr, 2003), the use of ethanol/gasoline blends up to 10% ethanol does not cause any problem to vehicles designed and built to operate with pure gasoline. In case of old vehicles with carburettor made of aluminium alloys, percentages of the ethanol above 5% may create corrosion problems for this item. Compatibility with plastics and elastomers is also cause for concern.

Both ethanol and gasoline are excellent fuels for Otto cycle engines but they have some differences that must be taken into account in designing and tuning the engines. Table A 3 below shows the main characteristics of both fuels.

Table A 3: Ethanol and gasoline characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Gasoline</th>
<th>Ethanol (E-100)</th>
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</thead>
<tbody>
<tr>
<td>Air / Fuel Stoichiometry</td>
<td>14.5: 1</td>
<td>9.0: 1</td>
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<tr>
<td>Specific Weight (20°C) (kg/m³)</td>
<td>± 770</td>
<td>± 810</td>
</tr>
<tr>
<td>Heat of Combustion (kcal / kg)</td>
<td>± 10,500</td>
<td>± 6,100</td>
</tr>
<tr>
<td>Octane Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MON</td>
<td>80 ~ 83</td>
<td>88 ~ 90</td>
</tr>
<tr>
<td>RON</td>
<td>90 ~ 96</td>
<td>105 ~ 90</td>
</tr>
<tr>
<td>(MON + RON)/2</td>
<td>≥ 87</td>
<td>≥ 95</td>
</tr>
<tr>
<td>Vapour Pressure (kPa)</td>
<td>55 ~ 70</td>
<td>≥ 40</td>
</tr>
<tr>
<td>Polarity of molecule</td>
<td>Not polar</td>
<td>Highly polar</td>
</tr>
<tr>
<td>Gum formation (deposits)</td>
<td>Reference</td>
<td>None</td>
</tr>
<tr>
<td>Anti-oxidant &amp; Detergent Additives</td>
<td>Required</td>
<td>Not required</td>
</tr>
</tbody>
</table>

Source: Joseph Jr, 2003

To guarantee vehicle operation from corrosion and deposit problem, it is very important to have the fuel ethanol meeting rigorous specifications. Brazil had a long learning process and the specifications in use today are the result of the lessons learned in this process, and they should be a good starting point for those countries initiating an ethanol fuel program. These specifications are shown in Table A 4.

Ethanol production technologies currently used in Brazil are quite adequate to produce ethanol within these specifications.
Table A 4: Ethanol fuel specifications in Brazil

<table>
<thead>
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<th>Characteristic</th>
<th>Unit</th>
<th>Anhydrous Ethylic Alcohol</th>
<th>Hydrous Ethylic Alcohol</th>
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<td>Aspect</td>
<td>-</td>
<td>Limpid</td>
<td>Limpid</td>
</tr>
<tr>
<td>Colour</td>
<td>-</td>
<td>Colourless</td>
<td>Light Yellow</td>
</tr>
<tr>
<td>Acid (as acetic acid)</td>
<td>mg/L</td>
<td>≥30.0</td>
<td>≥30.0</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>S/m</td>
<td>≥500</td>
<td>≥500</td>
</tr>
<tr>
<td>Specific Weight (20°C)</td>
<td>kg/m³</td>
<td>≥791.5</td>
<td>&gt;807.6 and ≥811.0</td>
</tr>
<tr>
<td>Ethanol Content</td>
<td>% v/v</td>
<td>≥99.3</td>
<td>≥92.6 and &lt;93.8</td>
</tr>
<tr>
<td>Hydrogen ion concentration (pH)</td>
<td>-</td>
<td>-</td>
<td>≥6.0 and ≥8.0</td>
</tr>
<tr>
<td>Evaporation Residue</td>
<td>mg/100mL</td>
<td>-</td>
<td>≥5.0</td>
</tr>
<tr>
<td>Hydrocarbons Content</td>
<td>% v/v</td>
<td>-</td>
<td>≥3.0</td>
</tr>
<tr>
<td>Ion Chloride (Cl⁻)</td>
<td>mg/kg</td>
<td>-</td>
<td>≥1.0</td>
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<tr>
<td>Ion Sulphate (SO₄²⁻)</td>
<td>mg/kg</td>
<td>-</td>
<td>≥4.0</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>mg/kg</td>
<td>-</td>
<td>≥5.0</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>mg/kg</td>
<td>-</td>
<td>≥2.0</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>mg/kg</td>
<td>≥7.0</td>
<td>Not specified</td>
</tr>
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</table>

Source: Silva Jr, 2003
Annex C: Cane juice pretreatment

Table A 5 and Table A 6 show four levels of intensity in the juice treatment processes, indicating the corresponding impacts on the investment costs of the system and the main fermentation parameters respectively.

### Table A 5: Alternatives of juice treatment for ethanol production

<table>
<thead>
<tr>
<th>Degree of Treatment</th>
<th>Process Description</th>
<th>Relative Investment Cost</th>
</tr>
</thead>
</table>
| Physical Treatment only | - Screening  
- Hydrocyclonic separation                                                     | 1.00                     |
| Physical plus heat shock and cooling | - Screening  
- Hydrocyclonic separation  
- Heating up to 105°C in heat exchangers  
- Cooling to fermentation temperature in plate heat exchangers  
- Screening  
- Hydrocyclonic separation  
- Sedimentation in large clarifiers  
- Cooling to fermentation temperature                                                     | 3.33                     |
| Complete treatment including physical operations, liming heat shock and sedimentation | - Screening  
- Hydrocyclonic separation  
- Liming  
- Heating up to 105°C in multistage direct contact heat exchangers  
- Sedimentation in trayless clarifiers  
- Partial cooling in flash tanks  
- Final cooling in plate heat exchangers                                                     | 6.64                     |

*Source: (Rossell, 1988)*

### Table A 6: Influence of different levels of juice treatment on fermentation parameters

<table>
<thead>
<tr>
<th>Fermentation Parameter</th>
<th>Physical treatment</th>
<th>Physical &amp; heat shock</th>
<th>Complete treatment</th>
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<tr>
<td>Productivity (kg of ethanol/m³ of vat per hour)</td>
<td>3.68</td>
<td>4.09</td>
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<td>Fermentation time (hour)</td>
<td>11.6</td>
<td>9.0</td>
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<tr>
<td>Alcohol concentration in wine (in volume)</td>
<td>6.5</td>
<td>9.5</td>
<td>11.7</td>
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<td>Antifoaming agents consumption (defoamer + dispenser) (kg of product/m³ of ethanol)</td>
<td>0.628</td>
<td>0.568</td>
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<tr>
<td>Sulphuric acid consumption (kg/m³ of ethanol)</td>
<td>6.344</td>
<td>3.212</td>
<td>6.994</td>
</tr>
</tbody>
</table>

*Source: (Rossell, 1988)*
Annex D: Evolution of fermentation technology in Brazil

The evolution of the fermentation technology in Brazil can be summarized by the variation of the fermentation time, yield and final ethanol concentration in the wine; Figure A 1, and Figure A 3 respectively show this evolution.

**Figure A 1: Evolution of fermentation time**

*Source: Fingerut, 2005*

**Figure A 2: Evolution of fermentation yield.**

*Source: Fingerut, 2005*
From the analysis of these three figures it can be concluded that the fermentation process in Brazil is a fully mature technology having reached the peak performance in the 90s. Although there is very little potential for further gains in yield and fermentation time reduction there are several possible improvements that can further reduce the production costs mainly through steam economy in the distillation plant, as discussed earlier in this report in section 4.2.2.
Annex E: Technologies for Ethanol Dehydration

Since distillation does not remove all water during ethanol production, additional water removal is achieved by dehydration processes. The three main dehydration technologies are used in Brazil: Azeotropic distillation, extraction distillation with monoethyleneglycol (MEG), and molecular sieves technology.

**Azeotropic distillation**
Cyclohexane is added at the top of dehydration column, and an azeotropic mixture of cyclohexane-ethanol-water is formed with a boiling temperature below that of ethanol. Ethanol at 99.7° GL is recovered at the column bottom and the azeotropic mixture is removed from the top, condensed and sent to a decanter, located in the upper half of dehydration column where two phases are formed. The upper layer is rich in cyclohexane and the lower one, rich in water; the upper layer is directed to the solvent recovery column. The solvent recovered at the top of this column is returned to the dehydration column to continue the process, while the water-ethanol mixture removed from the bottom is sent for ethanol recovery.

**Extraction distillation with monoethyleneglycol (MEG)**
In this technology, MEG is added to the hydrous ethanol and the MEG-ethanol-water mixture is sent to a distillation column where the ethanol evaporates to the top, and the MEG-water mixture is recovered at the bottom and then sent to another distillation column to recover MEG to be reutilized in the process.

**Molecular sieves**
The so called molecular sieves are a bed of zeolite beads, with the pores large enough to absorb the water molecules but small enough to avoid ethanol retention. Hydrous ethanol is vaporized before being sent to the molecular sieve columns; a two or three columns set is normally used to enable regeneration in one column while the system is in operation in the other column(s).

Regeneration is achieved by blowing ethanol vapour through the bed, or by the removal of the water from the zeolite beads; the mixture of ethanol and water is sent back to the distillation columns to recover the ethanol. Superheated steam may be used to regenerate the dehydration columns, and in this case the exhaust steam is blown to the atmosphere. The process is totally automated and dehydration/regeneration cycle lasts only a few minutes.
Annex F: Other Ethanol Conversion Technological Options

Various other technologies for the ethanol conversion have been developed depending on the substrate being fermented. The direct conversion of cane chips is currently being investigated. A variety of process configurations have been studied for conversion of cellulosic biomass into ethanol, and enzymatic hydrolysis of lignocellulosics provides opportunities to improve the technology so that bio-ethanol is competitive when compared to other liquid fuels on a large scale (Mosier et al., 2004)

1) **Separate Hydrolysis and Fermentation (SHF)**
Enzymatic hydrolysis generally consists of cellulose production, cellulose hydrolysis, hexose fermentation and finally pentose fermentation.

2) **Simultaneously Saccharification & Fermentation (SSF)**
This process in an improvement of the SHF, patented by the Gulf Oil Company and the University of Arkansas in USA. SSF is the most promising process for the production of ethanol from lignocellulosics. In SSF, enzymatic hydrolysis of cellulose to glucose and fermentation of sugars to ethanol are carried out simultaneously, in the same vessel. As sugars are produced, the fermentative organisms convert them into ethanol. The rate of hydrolysis is increased by reduced glucose-inhibition of the celluloses, in comparison to separate hydrolysis and fermentation, which results in higher productivity, or reduced enzyme consumption for the same productivity (Bollock et al., 2000). Another advantage of SSF is a lower capital cost due to the reduced number of vessels needed. One disadvantage of SSF is the difference in optimum conditions (pH and temperature) for hydrolysis and fermentation. The optimal pH is 4.8 for the cellulase enzyme system, and between 4 and 5 for the yeast cell. Accordingly, if the pH is maintained between 4.5 and 5 during the SSF, it is convenient for both the enzyme and the yeast. The optimal temperature is below 35°C for yeasts normally used for producing ethanol. Temperatures above 40°C lower the viability of most yeast cultures. The rate of hydrolysis is highest at temperatures in the 40-50°C range, as the cellulase enzyme system acts optimally at about 50°C. At lower temperatures, the rate of saccharification decreases considerably.

3) **Direct Microbial Conversion (DMC)**
DMC is an innovation of the SSF. The method involves conversion of cellulosic biomass to ethanol in which both ethanol and all required enzymes are produced by a single microorganism. The potential advantage of DMC is that a dedicated process step for the production of cellulose enzyme no longer remains necessary. DMC is not considered to be a leading process alternative today because there are no organisms available that produce both cellulose and other enzymes at sufficiently high levels, and also produce ethanol at the required high concentrations and yields. Most commercial applications for cellulose enzymes (for example in the textile industry) represent higher value markets than the fuel market. For this reason, there is a large leap from today’s cellulose enzyme industry to fuel ethanol industry. Moreover, due to the high cost of cellulose enzymes, acid hydrolysis technologies are preferred.
Annex G: Alternative ethanol production feedstocks

Apart from sugar cane based resource streams (i.e. cane juice, “A”, “B” and “C” molasses), as well as sweet sorghum, the following crops can also be used in ethanol production:

1) Cassava
Cassava is a very important staple food in many developing countries. It is a tuber crop capable to withstand droughts, civil unrests, and is often the sole source of food for the poor. Numerous studies have been carried out to test its feasibility as ethanol feedstock. For example, in Brazil in the early 1970s there was a large cassava-based ethanol programme of about 0.5 ML. However, cassava failed for a combination of reasons:
   i) high costs (cassava roots have to be first hydrolysed to fermentable sugars);
   ii) lack of experience with commercial plantations;
   iii) competition with sugar cane (Brazil is the world second largest cassava producer)

More recently countries like China, Thailand, and Philippines, have showed interest in obtaining ethanol from cassava. South Africa has also considerable potential but there is no experience or any major plan. Thailand in particular plans to produce ethanol primarily from cassava and cane molasses. One reason is that Thailand produces large surpluses (e.g., total production in 2002 was about 18-20 Mt/yr, of which 14 Mt/yr were exported compared with a domestic consumption 2 Mt); which are finding increasing difficulties to find markets; the same applies to molasses out of which there are about 1 Mt/yr of surpluses. To the best of our knowledge there are no other countries planning to use cassava as ethanol feedstock in any significant scale. India also failed in one plant to produce alcohol from cassava (Tapioca), on commercial scale, due to the high cost of the roots.

2) Wheat
Wheat is among the world’s most important cereals for human consumption58. Its use as a feedstock for large scale ethanol production is questionable, and can only be justified in specific circumstances, e.g., where surplus production is chronic as in the EU59. There are few areas in the world with large surpluses (e.g. Argentina, Australia, Canada) and whose main priority is to supply demand for human consumption and animal feed.

However, in the EU wheat is considered as a prime candidate for ethanol production, partly to get rid of the surpluses, and also because the possibility of using straw to provide the energy to run the plant. This could have a very positive impact on wheat as feedstock.

3) Sugar beet
Not many countries outside Europe produce sugar beet in any large scale. In Europe and particularly in the EU, there are good prospects for ethanol produce ethanol from beet for two main reasons:

58 World production for the 2004-05 harvest was about 650 Mt; the most important producer is the EU-25 with 137 Mt, followed by China with 90 Mt, according to FAO data.
59 Surplus production in the EU is largely the consequence of agricultural subsidies which are increasingly being questioned.
i) current surpluses, and
ii) possibilities of increasing productivity significantly. If the EU was to produce ethanol in large scale, sugar beet, and possible wheat, will be the major crops. In the longer term cellulose material could replace most other crops.

Syngenta Seeds (Chatin et al., 2004) spent seven years testing the feasibility of growing sugar beet in tropical countries, as an alternative to sugar cane. The company claims the following performance figures for this beet variety:

- **Productivity**: 60-80 t of beet/ha
- **Sugar content**: 14-19%
- **Crop season**: 5-6 months
- **Irrigation requirement**: 10,000 m³ / ha

Can be produced in alkaline or saline soils not suitable for cane.

In 2004, the first factory to process beet to ethanol was scheduled to be commissioned in India. Another was programmed to be built in 2005 in Colombia.

The experimental work also hinted that sugar beet could be used to expand the sugar/ethanol production in existing sugar cane mills. For the Brazilian conditions, where approximately 20% of the land for cane is available for several months before planting new cane, it may be worth investigating the alternative to plant this tropical sugar beet in these areas, and adapt the front end of the factory for this alternative feedstock.

4) **Maize (corn)**

Maize is a major world crop, particularly in the USA where it is the main source of ethanol, sweeteners, and multitude of other products. In other countries e.g. China and South Africa maize could play a significant supplementary role in the future as feedstock for ethanol, but it is unlikely that it will be in large scale due to high costs, lower productivity, high demand for other products such as sweeteners, etc. This could change significantly if ethanol can economically be obtained also from corn. The largest producer of alcohol from corn (maize) in USA is Archer Daniels Midland Company (ADM) with 55% of the total corn ethanol production in USA.

5) **Cellulose**

The potential of cellulose-based ethanol, e.g., wood, bagasse, corn straw, etc, has long been recognised as cellulosic material and is the most abundant biomass resource. For example, the USA market for cellulose-based ethanol was estimated at 1.8 BiL for ethanol-gasoline blends up to 2007, and more than 10 BiL after 2010 without any subsidy. The potential for neat ethanol in the long term was estimated at about 120 BiL (NRC, 1999; [www.eren.doe.gov/biopower](http://www.eren.doe.gov/biopower)).

But costs have remained stubbornly high (processes, technology, enzymes, etc.), and thus, the optimism of the late 1990s has given way to realism, that is, the recognition that ethanol from cellulose-based material is still at least 5 to 10 years away.

Sugar cane bagasse has also been a prime candidate for ethanol production, but with disappointing results so far. This together with its increasing use for generating heat and electricity raise some doubts. For example, if bagasse was successfully converted to ethanol, then other sources would have to be found to generate heat and electricity; this may outweigh any benefits from any extra ethanol production. An alternative could be to complement bagasse with cane tops and leaves and trash, and other crops...
residues, forestry residues, natural gas, etc. Bagasse is a cheap feedstock and is readily available at the mill and can be supplemented by sugar cane trash (tops and leaves) in those mills that are harvesting unburned cane. An extensive worked developed by CTC has shown that sugar cane trash can be recovered and delivered to the mill at a cost of less than US$15/tonne (dry basis), with a recovery efficiency higher than 50% (CTC, 2005). In India, about 15 mills having cogeneration projects are making use of trash balers to bale trash in the fields and transport it to the sugar mills for use as boiler fuel. It has been proved that trash has the same calorific value as mill wet bagasse. An experiment conducted in 1984 in Mauritius showed that cane tops, leaves and trash can be burnt in a bagasse cogeneration plant without major modifications, except for the feedstock preparation (Deepchand, 1986). In fact, the trash could be baled or pelletised for use during off-crop season for surplus electricity generation for sale to the grid.

One major equipment manufacturer in Brazil in association with the Sugar cane Technology Center (former CTC – Copersucar Technology Center) is developing an ethanol from cellulose technology, based on the Organsolv process with dilute acid hydrolysis. Several years of pilot plant operation led to the design and construction of a demonstration plant with a production capacity of 5,000 litres of ethanol per day; this plant is presently being commissioned in one mill in the State of São Paulo. Sugar cane bagasse is the feedstock and the design of the facility that takes advantage of the existing spare capacity in the fermentation and distillation sectors of the mill (a fairly common situation in Brazilian mills), to mix the hydrolysate liquid with the conventional broth and ferment all together. Laboratory experiments have indicated that conventional yeast strains can tolerate the contaminants from the hydrolysate (furfural, dimethyl furfural, organic acids, etc.) in percentage of the hydrolysate in the blend as high as 30%. This concept reduces considerably the initial investment cost since there will be no need to build hydrolysate purification system or new fermentation and distillation facilities.

In the first phase of the project only the six carbon sugars (hexoses) will be fermented; in the future the recovery and fermentation of the five carbon sugars (pentoses) will also be performed. The expected ethanol yields for the three phases (P1, P2 and P3) of the technology development are shown in Table A 7 for one dry tonne of bagasse.
Table A 7: Expected ethanol yields from one tonne of dry bagasse

<table>
<thead>
<tr>
<th>Process</th>
<th>P1 – Initial</th>
<th>P2 – Intermediate</th>
<th>P3 – Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hexose</td>
<td>Pentose</td>
<td>Hexose</td>
</tr>
<tr>
<td>Saccharification %</td>
<td>82</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>Fermentation %</td>
<td>90</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>Distillation %</td>
<td>99</td>
<td>-</td>
<td>99</td>
</tr>
<tr>
<td>Ethanol L/t</td>
<td>219</td>
<td>-</td>
<td>219</td>
</tr>
<tr>
<td>Total Ethanol L/t</td>
<td>218</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

Source: Dedini, 2003

From the results shown in Table A 7 and considering that 50% of bagasse can be saved and 50% of trash can be recovered (total 140 kg of dry fibre per ton of cane), from 30 to 50 litres of ethanol can be additionally produced per ton of cane, 35% to 60% increase from the present productivity of 85 L/t cane.
Annex H: Alternative uses of stillage

Apart from its use as fertiliser, animal feed and possible recycling, there are possibilities that vinasse can also be used for fungus production, to produce construction material and for energy production in incinerators.

Fungus production
There is little experience but it could be a promising alternative (high-value added products). Research was carried out at INT (Brazil's National Technological Institute) on fungi production from vinasse. Although the technology has not evolved from laboratory scale, it remains a promising alternative when high value products are sought.

Construction material
Fundamental studies conducted by experts on brick-making show that for some applications vinasse can be a useful building material. However, further research is still required as vinasse is a highly hygroscopic material and misuse of bricks made with such material, if exposed to water or humid weather, could cause the bricks to collapse.

Direct disposal by incineration
Basic research has been carried out by Cortez and Brossard (1997), who have experimented with incineration of pure and vinasse emulsions blended with heavy oils. Although vinasse incineration technology was already presented as being commercially viable in the early 1980s by some companies, e.g., Alfa Laval and Hollandase Constructive Group (HCG), in practice, it failed to live up to expectations. From the year 1950 onwards, the firm HCG installed boilers with special furnaces to burn concentrated vinasse in Holland, Czechoslovakia and Thailand. One such plant is still working successfully in the Banghikhan distillery in Thailand.

There are also other alternative disposal methods not yet tested in large-scale, e.g., ultra filtration and/or reverse osmosis, centrifugation, and production of single-cell protein.
# Partners

The Cane Resources Network for Southern Africa (CARENSA) was a Thematic Research Network supported by the European Commission's Directorate General for Research (DG-RES). The primary objective of the CARENSA work programme was to evaluate the potential for renewable energy from sugar cane and similar crops to support sustainable development and improve global competitiveness within the southern African Development Community (SADC) region.

The Stockholm Environment Institute (SEI) is an independent and non-profit international research institute specialising in sustainable development and environment issues. SEI was established by the Swedish government in 1989. Its research programme aims to clarify the requirements, strategies and policies for a transition to sustainability. SEI’s mission is to support decision-making and induce change towards sustainable development around the world by providing integrative knowledge that bridges science and policy in the field of environment and development.

Winrock International India (WII) is a registered not-for-profit organization working in three principal program areas: Energy and Environment (ENE), Natural Resource Management (NRM), Climate Change (CLC). Supported by a strong Outreach unit, WII in all its areas of work emphasizes the development of local institutions, leadership and human resources, and actively works towards building cooperation at all levels. Headquartered in New Delhi, WII works through a series of field-based and policy related projects across the country.

<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>University of Mauritius</td>
<td>Agricultural University of Athens, Greece</td>
</tr>
<tr>
<td>University of KwaZulu Natal</td>
<td>Food &amp; Agriculture Organisation of the United Nations</td>
</tr>
<tr>
<td>Interuniversity Research Centre on Sustainable Development, Italy</td>
<td>International Sugar Organisation</td>
</tr>
<tr>
<td>Biomass Users Network, Zimbabwe</td>
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</tr>
<tr>
<td>Centre for Energy, Environment and Engineering Zambia Limited, Zambia</td>
<td>University of Campinas, Brazil</td>
</tr>
</tbody>
</table>

This report along with related information is available on the CARENSA website: [www.carensa.net](http://www.carensa.net)