PROSPECTS FOR THE CONVERSION OF A SUGAR MILL INTO A BIOREFINERY

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Abstract

THE CONVERSION of a sugar mill into a multi-product sugarcane processing plant or biorefinery holds substantial potential for improving profitability in a sustainable way. This envisages a sugar mill producing not only sugar but a range of products which significantly improves its revenue stream. As well as products for direct use (e.g. ethanol), a biorefinery may also produce a range of chemical intermediates which represent the feedstocks for other products, in a similar way to the production of chemical feedstocks in an oil refinery. This paper considers the options for potential products and the processing steps necessary for the objectives to be realised. The optimum feedstock for a biorefinery could be significantly different from traditional sugarcane, bred for biomass not sucrose, and possibly augmented with other agricultural feedstocks. The present obstacles to the implementation of biorefinery schemes involving fractionation and hydrolysis of lignocellulosics as well as thermochemical treatments are identified. Economies of scale point toward the implementation of large plants to achieve economic viability. However, selected add-on options depending on the economics of individual processes provide the route for converting a sugar mill into a biorefinery in smaller, less capital-intensive steps. The successful implementation of some of the processing schemes discussed here could see a more profitable, diversified and expanded sugarcane processing industry.

Introduction

A sugar mill is in a sense already a biorefinery producing sugar and molasses as products and generating bagasse used as a fuel for use in sugar mill boilers. The true concept of a biorefinery, however, envisages a slate of products produced from sugarcane biomass, particularly fuels and chemicals, which together provide additional revenue. The concept converts a sugar mill into a sugarcane processing plant. Increasing attention is being given to this concept, either to increase revenue and profits, or to expand the agricultural industry, or purely to ensure survival in the face of increasing cost pressures.

Many claims have been made of how value-added products can be produced from sugarcane biomass. Apart from the production of paper from bagasse and cogeneration using bagasse as a fuel in boilers, very few of these are economically viable, apart from a few low volume niche markets. The challenge is to find those processes which, when incorporated into a biorefinery, will lead to products of value that justify the capital investment.

Rationale for a biorefinery

Lignocellulosic material is an excellent option compared to fossil fuels because it is an abundant, renewable resource that does not generate additional carbon dioxide in the earth's atmosphere. In addition, innovative expansion in the field of biofuel production would spur substantial job creation and stimulate the economy.

The active pursuit of energy production from sugarcane in the form of liquid fuels, chemicals and electric power can yield considerable benefits, including:

- A favourable impact on the generation of greenhouse gases and the environment.
- Use of renewable resources for energy production.
- Reduction in a reliance on imported fuels.
- Incentive to expand agricultural production.
- Elimination of the burning of cane.

As the sugarcane industry is a major contributor to the economy of most sugar producing countries, the effect of a vibrant production sector has considerable impact because it also affects the support industries (agricultural equipment, process plant suppliers, providers of services and consumables). The bottom line for a successful development of biomass processing is:

- The sugar industry diversifies its product base by producing energy products and chemicals as well as sugar.
- Expansion rather than contraction of the sugarcane industry is envisaged, with a substantial economic impact.

What is a biorefinery?

Increasing attention is being given to the development of a sugarcane biorefinery. Research efforts are aimed at producing fermentable sugars from bagasse and CLM (cane leaf matter) and also at gasifying the material for use in electrical energy or liquid fuels production. A biorefinery may parallel the conventional refinery in producing building blocks for further processing to chemicals. The conventional refinery may produce ethylene as a building block; a biorefinery may produce chemicals via biological or chemical conversions for use as intermediates. The US National Renewable Energy Laboratory (NREL) has identified the following most promising 12 building blocks:

- 1,4-Succinic, fumaric and malic acids.
- 2,5-Furan-dicarboxylic acid.
- 3-Hydroxy-propionic acid.
- Aspartic acid.
- Glucaric acid.
- Glutamic acid.
- Itaconic acid.
- Levulinic acid.
- 3-Hydroxybutyrolactone.
- Glycerol.
- Sorbitol.
- Xylitol/arabinitol.

Large-scale usage of bagasse or other biomass for ethanol or chemicals is not yet a reality, although many different schemes have been devised in the laboratory. Maximum value from bagasse can in theory be obtained by separating bagasse into its three major components, cellulose, lignin and hemicellulose, and deriving products with high value from them. Fractionation of bagasse in this way is difficult, but active research and recent technological improvements are likely to make commercialisation possible in the future.

Advantages of a sugarcane biorefinery

A raw sugar mill already has the infrastructure in place for collecting and processing sugarcane biomass. This is a major advantage over other lignocellulosic processing options using e.g. corn stover or forest wastes. Selected add-on options depending on the economics of individual processes provide the route for converting a sugar mill into a biorefinery. In theory too, it is possible to vary the mix of products to maximise revenue in the face of dynamic market conditions.

In addition, a sugarcane biorefinery is independent of outside fuel resources, both reducing processing costs and exposure to fuel cost variability.

Sugarcane is a prolific biomass producing crop, having a photosynthetic capacity significantly larger than most other crops. This is an inherent advantage of a sugarcane based industry. Well-managed cane in Brazil fixes between 20 to 30 t DM/ha/y, notably greater than that of undisturbed 'natural' vegetation of up to 5 t DM/ha/y) (Junginger *et al.,* 2006). In addition, biofuel crops grown in tropical regions perform better than crops grown in temperate climates in terms of greenhouse gas emission reductions, e.g. Brazil cane 80 to 90%, vs. 20 to 50% for crops such as rape seed and corn (Junginger *et al.,* 2006), compared to gasoline.

With a solar efficiency from 1 to as much as 3.3% (Legendre and Burner, 1995), sugarcane produces more biomass DM per hectare than any other crop species. It can, therefore, have a strong positive influence on the environment. Rozeff (1993) estimated for South Texas conditions O_2 production at 37 t/ha/y of sugarcane and CO_2 fixation rate at 49 t/ha/y, more than three times that for mid-latitude temperate forests.

Sugarcane biomass production

Biomass composition

All biomass consists of three key organic constituents, specifically cellulose, hemicellulose, lignin and additional minor constituents that include extractives and inorganic materials. The cellulose component has an average molecular weight between 3 and 5×10^6 g/g·mol and is a linear macromolecule, consisting of polymeric β-(1,4)-D-glucopyranose building blocks linked together by (1→4)-glycosidic bonds, that is similar in all forms of biomass, apart from its degree of polymerisation. Cellulose is insoluble in water and comprises almost half of the cell wall material that provides the skeletal support structure of biomass. Cellulose undergoes thermal degradation at 319°C (Dinu and Saska, 2007). Typically, cellulose exhibits a high degree of crystallinity and has a relatively ordered structure that results in fibrils. In contrast, the character of the hemicellulose and lignin fluctuates with respect to the biomass type.

Hemicellulose, unlike cellulose, has an amorphous, branched configuration with a low degree of polymerisation; it is soluble in dilute alkali. It exhibits lower thermal stability than cellulose, decomposing at approximately 279°C (Dinu and Saska, 2007) ostensibly due to the absence of crystallinity and order within the hemicellulose framework. Besides furan derivatives, acetic and formic acids and some five carbon sugars are formed in abundance during hemicellulose thermal degradation. Xylan is the principal hemicellulose found in sugarcane.

Lignin is an amorphous and randomly linked, highly branched phenolic compound. Lignins exist as aromatic polymers in the cell wall structure, and are commonly attached to neighbouring cellulose fibres to create a lignocellulosic complex. They provide stiffness, disease resistance and water resistance. Both lignins and lignocellulose are exceptionally resilient to microbial decay or chemical conversion. Nevertheless, lignocellulose can be degraded and the lignin portion separated upon treatment with concentrated sulfuric acid. Dehydration is the most common lignin degradation mechanism and nearly all low molecular weight products derived from lignin contain phenolic hydroxyl moieties. The primary pyrolysis decomposition products of lignin are phenols and aromatic hydrocarbons.

The relative quantities of the three components cellulose, hemicellulose and lignin vary considerably depending on the cane variety, the age of the cane, the growing conditions etc. There are also small quantities of inorganic components present in the cellular structure of the cane, namely silica and calcium. Some analyses of cane fibre are given in Table 1. The composition of fibre is not significantly changed during extraction.

Table 1—Typical analyses of cane fibre (in g/100 g dry substance).

	Clarke (1998)	Purchase (1995)
	Range	Average
Cellulose	40—58	40
Hemicellulose	24—32	33
Lignin	13—22	22
Ash/other	1—4	5

Quantity of bagasse and CLM

The quantity of bagasse is determined primarily by the fibre content of the cane being processed. Nearly all of it ends up in the bagasse, but some finds its way into the raw juice going to the factory, which leaves the factory in the filter cake together with added bagacillo. In practice a small proportion of the bagasse is put aside in a bagasse store for recovery and use during start-up or shut-down, or for use during mill stops. This should be somewhere between 5 and 10% of the total amount of bagasse produced. Thus the amount of bagasse available may be anywhere between 22 and 35 t/100 t cane (wet basis), but is more usually in the range 25 to 30 t/100 t cane.

Leaves and tops are a potential source of fibre and fermentable substrates. However, in most instances, cane leaves and tops (CLM) represent a disposal problem. They are an undesirable component of the cane and processors encourage the delivery of cane with minimum CLM. This means that it should ideally be left in the field. In some countries CLM left in the field has value in preserving moisture, restricting weed growth, and improving the organic content of the soil. However, in areas like Louisiana, extraneous matter left in the fields keeps the temperature of the soil down, delaying germination of the next ratoon and reducing cane yields (Viator *et al.,* 2005). It is therefore common practice to burn this material in the fields or rake it away from the sugarcane roots.

The quantities of tops and leaves associated with cane are very variable and quantities reported are affected by a variable moisture content. The amount of tops and leaves is better represented in terms of dry matter in relation to the amount of cane, because this measure is independent of the moisture content of the tops and leaves. Leaves and tops expressed on a dry matter basis have been estimated in Brazil to average 140 kg dry matter / t of whole stalk cane, varying between 110 and 170 kg/t cane (Hassuani, 2001). Purchase and de Beer (1999) reported that tops and leaves represent on average 190 kg dry matter / t mature clean cane stalk. An average of about 150 kg dry matter in leaves and tops /t clean whole stalk cane can be assumed.

Potential surplus bagasse production.

It is possible to modify the steam requirement of a sugar mill to be able to generate a surplus, if the surplus can be sold for a by-product or other enterprise. Easy and low-cost modifications can be made to generate a small surplus; as the required surplus increases, the cost of additional modifications becomes greater until at some point the cost of producing a greater surplus is not justified by the cost.

There are some sugar mills around the world which produce enough surplus to supply large paper mills, without burning significant amounts of supplementary fuel. Reid and Rein (1983) showed that a sugar mill can be relatively easily configured to provide one-third of its bagasse for sale to an adjacent paper mill. In theory, with high pressure high efficiency boilers and minimised process steam usage, larger surpluses of around 45% are possible.

Potential expansion with high biomass cane

The results of a project in the late 1970s and early 1980s to evaluate non-commercial ‘high fibre’ varieties of sugarcane for biomass production are shown in Table 2 as a comparison between the predominant commercial cane CP 65-357 and L 79-1002, the best among the high fibre canes tested (Giamalva *et al.*, 1984).

Table 2—Comparison of biomass yield of regular and 'high fibre' cane yields in t/ha/y.

Year	CP 65-357	L 79-1002
1976	83	182
1977	61	191
1978	49	204
1979	54	233
1980	43	247

The total biomass yield was considerably higher than that of the commercial varieties and, while the yield of the latter drops off rapidly and the cane has to be replanted after three years, the high fibre cane yields persisted into or even after the sixth year. The other benefits were not as well documented but are potentially also very significant (Clarke *et al.*, 1982; Giamalva *et al.,*1984), namely:

- Significant reduction or even elimination of the need for herbicides.
- Reduction of annual cost of production to about ½ that for commercial sugarcane.
- Increased freeze tolerance.
- Early maturation, before conventional sugarcane.

The last two items could open ways to extending the harvesting season and expansion of the production area. Giamalva's results were later confirmed in Louisiana by Legendre and Burner (1995) and in Florida.

More recently, three energy cane candidates for commercial release are being considered in Louisiana, with an average yield 25 to 33% more tonnes dry matter/ha than the current most commonly used variety (LCP 85-384). The selection criteria for energy canes are different from those normally used. Sucrose content, maturing, post-freeze deterioration, shading and ripener response are not important; ratoon ability is, however, far more important and total sugar rather than recoverable sugar is selected. Its ability to grow on what would otherwise be regarded as marginal land is also selected.

Prospects for augmenting quantities for bioprocessing using other crops

In order to make maximum use of the expensive capital equipment, efforts could be made to increase the input mass by using not only bagasse, cane tops and leaves, but other crops as well.

Research has shown that sweet sorghum does have potential as a biofuel source (Arthur *et al.*, 1979; Jackson *et al.*, 1979). More recent work (Tew and Cobill, 2006) has shown that total dry matter in sorghum trials can reach values as high as 34 tonnes/ha, with sugar: fibre ratios between 30:70 and 50:50. From these results, it was estimated that theoretically 8700 L ethanol could be produced from the sugars and the fibre per ha. The crop is drought resistant and has potential to integrate with the cane crop to assure an augmented supply of biomass to a processor. It is quite possible that the processing season can be extended by processing sorghum in the same facility as cane.

Several *Miscanthus* spp. clones have been evaluated at the Sugarcane Research Unit near Houma in Louisiana. Preliminary results show yields ranging from 64 to 77 tonnes/ha. Miscanthus is cold tolerant and not a tropical plant. It shuts down at high temperatures but is fast growing and could be used as a supplement feedstock in the spring.

Processing options for the conversion of sugarcane biomass to fuels

Mature biorefineries will necessarily process all the crop material. Although a start-up system at a sugar mill will most likely initially operate on the bagasse already available, because the technology for collecting and handling this material is already in place, a relatively simple change in farm operations will allow collection of the entire plant, with allowance for different transportation characteristics.

The options available for processing biomass to fuels are shown in Figure 1. The hydrolysis of lignocellulose to sugars is one of the main options. It leads to the production of fermentable sugars, both C_5 and C_6 sugars, which are fermented to ethanol or other products, paralleling the direct processing of corn or sugar to ethanol. The valorisation of the aromatic lignin portion remains a challenge, despite the efforts of numerous research groups.

The other main thrust is thermochemical conversion, which covers gasification and pyrolysis. The products may lead to a number of different products, as Figure 1 shows. A further alternative is the use of syngas in the direct production of electric power.

The anaerobic digestion route shown in Figure 1 does not appear to be a good prospect at present for sugarcane biomass. It is more appropriately applied to animal wastes and domestic wastes or landfill sites.

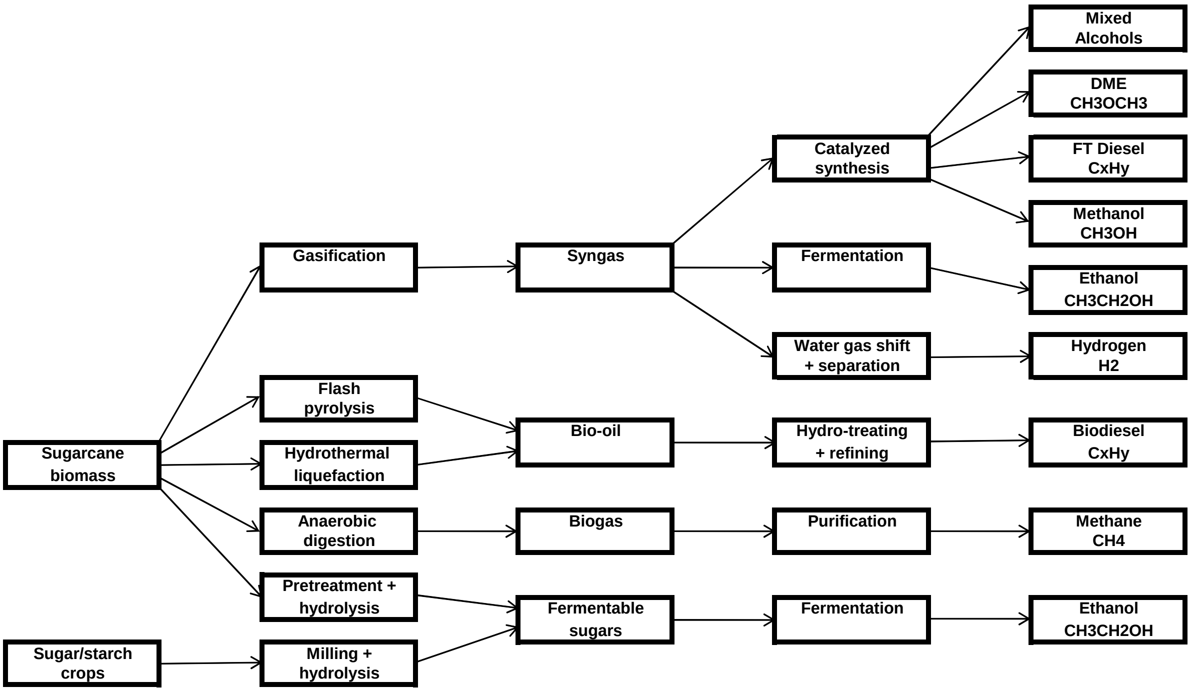

Fig. 1—Various routes for production of fuels from biomass.

Hydrolysis and fermentation products

Enzymatic hydrolysis of the carbohydrate portion of lignocellulose to xylose, glucose and cellobiose is a technically versatile and flexible means for utilising lignocellulosic biomass. The sugars produced can be either used directly in the food and biotechnology industries, or serve as platforms for producing a variety of bulk and specialty chemicals, including ethanol. A biorefinery based on cellulosic conversion using enzyme hydrolysis might use a scheme as shown in Figure 2.

Pretreatment methods for bagasse and CLM

By natural design, cell wall polysaccharides are more difficult to break down than storage carbohydrates like starch. A large number of pretreatment methods have been researched for improving cellulose hydrolysis from lignocellulosic biomass. All are aimed at making the constituents more readily available to the treatments following (Mosier *et al.*, 2005). Pretreatment results must be balanced against their impact on the cost of downstream processing steps and the trade-off between operating, capital and biomass costs.

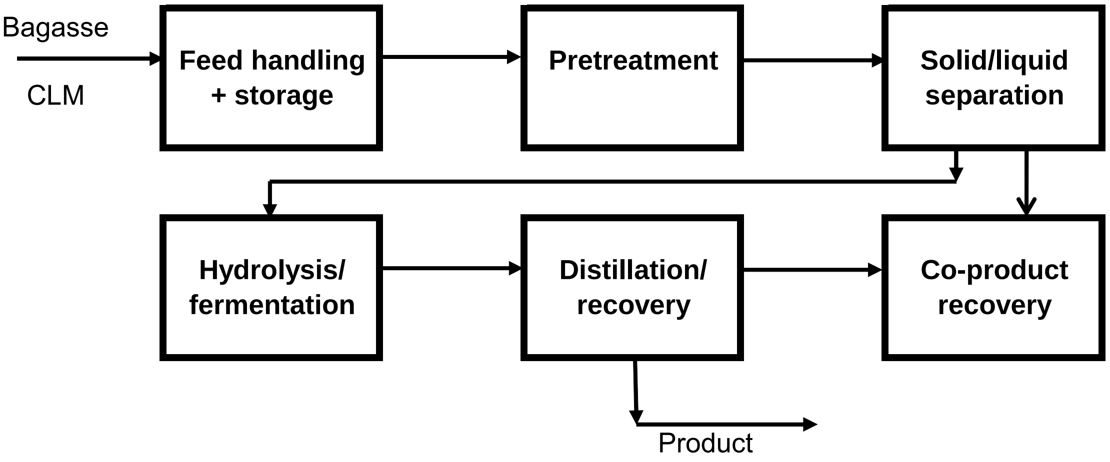

Fig. 2—Schematic of the hydrolysis route for a lignocellulose based biorefinery.

Work at Audubon Sugar Institute has shown that removal of 40% of the lignin is sufficient to achieve high hydrolysis yields. Pretreatment options are:

Mechanical pulverisation

The goal of mechanical pulverisation is to reduce particle size, as increased surface area leads to improved cellulose hydrolysis; the crystallinity of cellulose is reduced, but these methods generally are high cost and do not remove the lignin or hemicellulose.

Acid treatment

Dilute acid treatment removes hemicellulose and alters the lignin structure. Strong acid can hydrolyse cellulose and reduce the crystalline region but degrades glucose. In addition, the concentrated acid process requires recycling and reuse of the acid, a technically feasible yet expensive process. Acid usually has a greater effect on the hemicellulose and lignin content than alkali treatments (Fox *et al.*, 1987). Acid treatments normally result in a range of by-products, such as furfurals, which can act as downstream inhibitors in alcohol production.

Autohydrolysis (steam explosion)

This is an efficient pretreatment method for some lignocellulosic biomass. Biomass is heated for a few minutes in a pressure vessel and then the pressure is decreased rapidly. The acetyl groups that are an inherent part of most biomass are rapidly released during the reaction, reducing the pH of the environment and enhancing hemicellulose hydrolysis. Hemicellulose and lignin degradation increase the ability to hydrolyse the cellulose enzymatically (Ramos and Fontana, 1996; Martín *et al.,* 2002; Grous *et al.*, 1986).

Ammonia Fibre Explosion (AFEX)

AFEX treatment is similar to the autohydrolysis process and is usually conducted at 90°C for 30 min (Sun and Cheng, 2002). It is a simple process, does not produce fermentation inhibitors and has a short process time. It is effective in the treatment of corn stover but, with sugarcane bagasse, the AFEX process conditions are less effective (McMillan, 1994; Audubon Sugar Institute, unpublished). The AFEX process requires a 98% or higher ammonia recovery efficiency if the process is to be economical.

Alkali treatment

Alkali reduces the lignin and hemicellulose content of biomass, increases the surface area, allowing penetration of water molecules to the inner layers, and breaks the bonds between hemicellulose and lignin-carbohydrate (Gratzl and Chen, 2000; Fox *et al.,* 1987). Dilute sodium hydroxide is used in pulping bagasse, but cheaper treatments involving the use of lime or ammonia are preferred.

Oxidative delignification

Hydrogen peroxide can solubilise about half of the lignin and most of the hemicellulose in biomass (Azzam, 1989).

The goal of pretreatment is to reduce the cost of hydrolysis. Most models for conversion of pretreated cellulose to sugars require the use of 'commercially available' cellulases. These are cocktails of several cellulolytic enzymes that can convert cellulose and hemicellulose to their component sugars. The US Government has put much effort into arranging commercial supplies of these enzymes. The estimate for enzyme cost is between 4 and 6 US cents/L ethanol produced.

Work is also in progress to establish consolidated biomass processing (CBP) as a viable process, in which a single organism produces enzymes for hydrolysis and for the fermentation of C_5 and C_6 sugars (Weimer, 2006).

Fermentation

All fermentations rely on the biochemical pathways employed by micro-organisms to convert the starting substrates into the desired products. The gold standard for the cellulosic-biomass fermentation process is a micro-organism that will simultaneously convert xylose (from hemicellulose) and glucose (from cellulose) into ethanol; otherwise hemicellulose conversion may have to be separated from cellulose conversion and the fermentation broths pooled prior to distillation.

The conversion of glucose to ethanol by *Saccharomyces* is a standard industrial process and no change would be expected using cellulose derived glucose compared to starch derived glucose. The hemicellulose conversion is less well studied. Significant work has been conducted on *Zymomonas mobilis* (bacteria) based fermentations and a number of mutants of *Zymomonas* capable of fermenting xylose to ethanol have been developed (Lee and Huang, 1995).

Yeasts capable of fermenting xylose, such as *Pichia stipitis* are also potential organisms for hemicellulose conversion and are being widely studied (Dominguez *et al*., 2000). Genetically engineered strains of *E. coli* (Ingram *et al*., 1999) and *Saccharomyces* (Krishnan *et al*., 1999) are a few of the strains tested for ethanol-production. Genetic tools now provide the means to modify the properties of organisms and eliminate some of the biological limitations responsible for complexity with lignocellulosic feedstocks. There is room for significant improvements in this area. Both separate processes of pretreatment and fermentation and combined processes of pretreatment/fermentation processes are being studied.

Yields expected

Theoretically a 100% dry solids bagasse could yield about 37% alcohol by mass, depending on the composition of the bagasse. A tonne of dry bagasse can be expected to produce a maximum of 470 L ethanol. Current estimates are 315 L/tonne dry matter in bagasse. Currently, there is no technology available to handle solid state ethanol fermentations at 100% solids.

The maximum bagasse solids level that currently can be handled by fermentation is about 20%. This, with 100% efficiency of conversion and fermentation, would produce a broth containing about 7% ethanol.

Effluent handling

Alcohol stillage disposal is a major consideration for any alcohol production facility. Quantities are large and the stillage is normally a high BOD material, acidic in nature, containing all the salts and minerals used in the fermentation, as well as those organic materials produced during the fermentation. A molasses stillage is particularly rich in useful components.

A lignocellulosic stillage would be expected to be of somewhat lower BOD and value. Treatment and disposal of this material is a major consideration in any cellulosic ethanol plant. A sugarcane bio-processing plant can probably effectively integrate evaporation into sugar mill systems to concentrate the stillage, reducing volume and increasing the value of the material.

Thermochemical conversion

Thermochemical conversion of bagasse in a conventional sugar mill has traditionally implied the utilisation of bagasse as boiler fuel for the production of electricity and steam. There are other applications referred to as thermochemical processes which entail pyrolysis, gasification, liquefaction, and carbonisation methods either individually or in combination (Soltes, 1988). The distinction between these processes can often be somewhat blurred. The main products from gasification and pyrolysis are syngas and pyrolysis liquids respectively. Syngas is a combustible mixture of carbon monoxide, hydrogen, carbon dioxide and methane. Pyrolysis liquids commonly refer to dark mobile liquids that can be burned in boilers as liquid fuel and that more recently have been successfully fractionated into various chemical classes for use in other applications.

Pyrolysis

Pyrolysis can be defined as the thermal degradation of organic matter in the absence of added oxidising agents though, in practice, it is difficult to attain an entirely oxygen-free atmosphere. The pyrolytic decomposition of biomass generates gases (CO_2, CO, H_2O, H_2), a complex volatile phase (condensable gases), and a carbonaceous char that contains inorganic constituents. The volatile fraction can be condensed to form an aqueous distillate, known as pyroligneous acid. This can be further fractionated into soluble and insoluble organic phases. This latter phase is a highly oxygenated crude oil (Brown, 2004) that is frequently referred to as bio-oil, or pyrolysis oil. The product yield and composition are dependent on the chemical composition of the biomass feed, particle size, heating rate, reactor temperature, and reaction time. In conventional pyrolysis, gas production is favoured under higher temperatures and longer residence times, whereas higher char formation is promoted at lower temperatures and slow heating rates (Klass, 1998).

Gasification

Gasification occurs at high temperatures (600–1000°C) in three distinct steps in which the biomass feedstock undergoes a thermal decomposition to produce a synthesis gas (also known as syngas) comprised primarily of carbon monoxide and hydrogen in various ratios. Other gas-phase products obtained from biomass gasification include carbon dioxide, methane, and water. The gasification process involves an initial rapid pyrolysis of the biomass feedstock at high temperature followed by partial oxidation to form primarily gas products with varying quantities of char and tar, both of which can foul surfaces and plug pipes in the cooler sections of the system. The last stage of gasification involves the removal of char and tars from the gas product stream. Complete removal of the char can be effected with the use of filters since it is a solid particulate. Unfortunately, even the most sophisticated filtration devices can remove only 90% of the tar in the gas stream (Asadullah *et al.*, 2001). Generally gas clean-up still represents a technical challenge. The final product distribution and gas composition depend on both the reactor type and the reaction conditions, including the heating rate, residence time, temperature, and internal atmosphere (Zanzi *et al.*, 2002).

It is possible to achieve higher levels of electricity generation by the use of combined-cycles employing gas turbines as well as conventional boilers and steam turbines. The syngas is burnt in a gas turbine which drives an electrical generator. The hot exhaust gas passes to a waste-heat boiler operating at a suitably high pressure so that the steam generated can flow through another turbine before passing to process. This turbine drives a second electrical generator. The temperature in the gas turbine is higher than the steam temperature entering a conventional turbine, so a greater overall enthalpy drop is achieved. These combined biomass-driven cycles are commonly referred to as biomass integrated gasifier/gas turbine combined cycles (BIG/GTCC, or simply BIGCC). It was calculated that the Mauritian sugar industry could increase their total exportable electricity by 234% to 355 kWh/t of sugarcane if they employed combined cycle cogeneration gasification of both sugarcane bagasse and cane leaf trash (Kong Win Chang *et al.*, 2000).

Gasification of moist bagasse dilutes the resultant fuel gas with water vapour, increasing the volume and lowering the heating value. The bagasse is usually therefore dried using the final gas from the waste heat boiler. Seven tests conducted at a 2 MW pilot plant constructed by Termiska Processor AB (TPS) of Sweden demonstrated that sugarcane bagasse and CLM are suitable feedstock candidates for the gasification process (Morris *et al.*, 2002). A conceptual blueprint of a BIGCC plant integrated into a conventional Brazilian sugar mill was designed based on the outcome of the previous tests.

If the Fischer-Tropsch process is used to produce fuels, about 20% of the energy in the biomass is needed to gasify and another 20% of the energy in syngas is used to process through Fischer-Tropsch. Fischer-Tropsch only makes economic sense above 100 t/day processing rate.

Evolution of a sugarcane mill into a biorefinery

As the fuel, energy and chemical production options become economically attractive, the conventional sugarcane mill will change by degrees. Potential evolutionary routes which can be envisaged are considered below:

(1) A conventional sugar mill produces only sugar and molasses, and generates sufficient power and steam to cater for its own needs. A modification of this basic case sees a mill producing direct consumption sugar or refined sugar through a back-end refinery and exporting surplus power for sale.

(2) A sugar mill with an ethanol plant attached, producing sugar and ethanol, or only ethanol, is the norm in Brazil. The ability to produce both sugar and ethanol is the preferred option, for a number of reasons.

- It retains some flexibility to alter within limits the proportions of sugar and ethanol produced, to maximise revenue.
- There are processing advantages, enabling good quality sugar to be produced more cheaply by diverting lower purity streams to ethanol production.
- The ability to produce A molasses and/or B molasses enables fermentable sugars to be stored in this form for operation of the distillery in off-crop.

The stillage produced is returned as a fertiliser to the cane fields in countries like Brazil and Zimbabwe. This is unlikely to be practical in many countries, and anaerobic digestion producing biogas for use in the boilers is likely to be the most common treatment option. On average, 185 m^3 of biogas containing 60% methane is produced per m^3 of ethanol; this is roughly equivalent to the energy value of 0.69 t bagasse (Silva Lora *et al*., 2006). This helps to maintain low energy costs in off-crop processing periods.

(3) The Brazilian option discussed above is unlikely to be economical in sugar producing areas where the sugar price is higher than the price which ethanol attracts. In this instance, production of the maximum amount of electrical energy may be attractive and is already being used to advantage in a number of sugar industries. Various steps may be taken within the sugar mill to maximise generation of power, as they appear economically advantageous, including:

- Replacement of old inefficient boilers with more efficient high pressure boilers, typically 60 to 80 bar pressure.
- Replacement of steam turbines with electric drives.

- Reduction in process steam usage, through factory modifications.

In this scenario there is an incentive to bring the whole cane plant to the mill, to maximise the fuel supply. The alternative of bringing the tops and leaves left in the fields separately is sometimes considered to be a preferable option. However, bringing the whole cane has the following advantages:

- The leaves and tops can be removed separately at the mill pneumatically, with a reduced loss of cane relative to mechanical harvesting.
- A cleaner cane supply to the mill is achieved with capacity, recovery and sugar quality benefits.
- Leaves and tops are added back ratably into the bagasse supply. This mitigates the propensity of leaves and tops burnt on their own to cause slagging and fouling in the boilers due to the higher alkali metal content.

(4) There are some substantial advantages in combining ethanol production outlined in scenario (2) with the maximum power generation case described above. The cogeneration may be practised all year round, given the right season length, supplying the distillery with process steam and cogenerating power for export.

Any scenario producing power for export can be enhanced through gasification of bagasse, and making use of an integrated bagasse gasification and gas turbine combined cycle (BIG/GT). Silva Lora *et al.* (2006) show that this case can lead to the generation of surplus energy of 210 kWh/t_c compared to 74 kWh/t_c in the previous case. There are no BIG/GT plants currently operational in sugar mills, and the cost of gasification relative to the entire revenue available is still an unknown. However, the large increase in potential power generation requires that this option be given increased attention.

Maximum ethanol production can be achieved, with or without some sugar being manufactured as per scenario (3) with maximum cane biomass delivery, but producing only enough power for the biorefinery, and diverting surplus bagasse to ethanol manufacture, via enzyme hydrolysis and fermentation. The overall processing scheme is shown in Figure 3. This shows the integration of the activities, the extent of each being optimised to yield maximum profit.

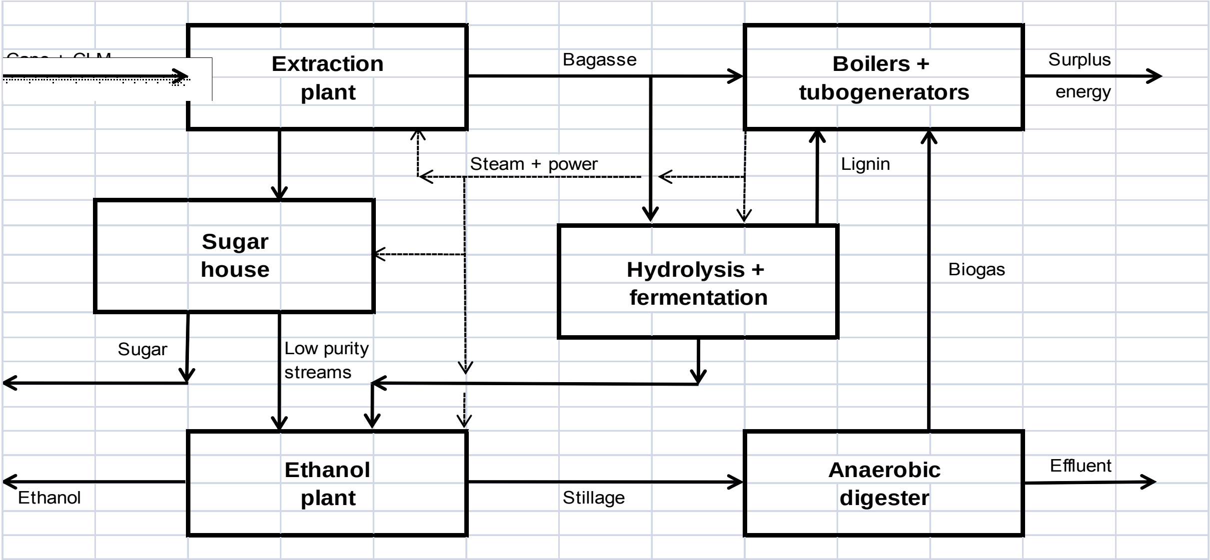

Fig. 3—Integration of ethanol production into a sugar mill.

(5) The true biorefinery will follow the outline of scenario (6), but will produce other products instead of or in addition to ethanol. It may also involve gasification rather than hydrolysis and fermentation, opening the possibility of a wider range of value-added products. All options other than scenarios (1) and (2) are improved by increasing the amount of biomass fed to the mill. It is logical therefore to change to varieties of cane which will give increased quantities of sugarcane biomass per unit area of farmland. This opens the door for high energy cane, bred for biomass rather than sugar yield.

Economic considerations

There is an essential difference between the economics of a lignocellulose ethanol plant and a conventional plant using corn or sugar. The economics of the latter are highly dependent on the cost of the feedstock whereas, with a lignocellulose feed, the feedstock cost is low and the capital and processing costs determine its economic viability. The cost of producing bioethanol is overwhelmingly associated with fuel processing. Bioethanol provides a great opportunity for novel processes to reduce costs. Another essential difference is the diversified and perhaps more flexible nature of a biorefinery relative to a single product plant.

Economies of scale have always favoured large sugar mills rather than small mills. The latter are the first to close when harsh economic conditions prevail; the remaining mills get larger and more profitable. Economies of scale are even more important with a biorefinery, and NREL consider that a plant processing biomass should process at least 2 000 t DM per day to be profitable. Assuming that a mill can make one-third of its bagasse available as surplus, this implies that a mill processing 40 000 t/day is required to produce this amount of surplus bagasse or else the combined output of a number of adjacent mills is required.

Sugar mills are actually biorefineries, taking biomass (sugarcane) and producing sugar, bagasse and energy. It takes relatively little modification, with the appropriate technology, for a sugar mill to add another product line. Table 3 compares the cost of producing alcohol in a sugar mill, where credit can be taken for existing facilities and operations, versus a stand-alone corn stover ethanol plant. The information is based on the study of McAloon *et al.* (2000).

Table 3—Estimated operating costs for production of fuel alcohol (1999 US$ per US gallon) for a corn stover cellulose operation and a bagasse sugar mill operation.

	Corn Stover	Bagasse
Feedstock	0.45	0.10
Feed handling	0.05	0.05
Pretreatment	0.20	0.20
Enzyme production	0.15	0.15
Fermentation	0.15	0.15
Distillation	0.02	0.02
Solids separation	0.05	0.05
Wastewater treatment	0.05	0.05
Product storage	0.03	0.03
Boiler, steam requirements	0.25	–
Utilities	0.10	–
Total cost per gallon	$1.45	$0.85

The numbers in this table make some assumptions about improved technology. The NREL planning suggests that, under current conditions, ethanol can be produced from corn stover at $2.50/US gallon ($0.66/L). This is expected to reduce to less than half this cost by 2012. The numbers in Table 3 suggest that the cost of producing ethanol from sugarcane biomass is likely to be somewhat lower, particularly as the cost of feedstock material is so much lower. It is evident from the Brazilian sugarcane and the US corn experiences that progressive reduction in production costs are a consequence of on-going large scale production of ethanol.

The cost of enzymes may be higher than the table suggests. Two of the first semi-commercial lignocellulosic plants proposed (by Iogen and Celunol) make allowance for their in-house production of enzymes rather than rely on enzyme suppliers.

Role of molasses in enhancing economics

Production of ethanol from sugarcane molasses is a well established industrial process. Molasses currently is sold mainly to the animal feed market, but could readily be moved to alcohol production. Table 4 gives the estimated volumes of molasses and ethanol that can be produced from processing a million tonnes of sugarcane.

Table 4—Potential alcohol production from molasses produced from a million tonnes of sugarcane processed.

Material produced	
Blackstrap molasses	35 000 tonnes
Ethanol	9 275 000 L

Molasses can be blended with sugars produced from lignocellulose, expanding the molasses supply and taking advantage of the nutrients available in the molasses to enhance fermentation. A molasses fermentation/distillation operation at an existing sugar mill, by addition of a pretreatment system, may act as a demonstration facility for lignocellulose/ethanol production with minimum risk.

Case study for Louisiana

The case of a biorefinery established at one of four large mills in the Teche area of Louisiana can be considered. It is estimated that a combined bagasse surplus of 430 000 t/y or 208 000 t DM/y could be produced. This could be increased to 593 000 t DM/y if 70% of the CLM left in the fields is brought to these mills. This represents a plant size of about 2 000 t DM/day.

Details of the quantities involved, based on 2003 crop figures, are shown in Table 5. The calculations are based on the following assumptions:

DM in CLM is 14% of the mass of clean cane

Cane currently delivered has 10 kg CLM/100 kg cane

Collection efficiency of CLM left in the fields is 70%

Conversion of cellulose and hemicellulose to sugars is 90%

Yield of glucose to ethanol is 88.5% of stoichiometric

Yield of C_5 sugars to ethanol is 80% of stoichiometric

These numbers indicate that 235 ML/y of ethanol can be produced from this plant, or a distillery of about 780 000 L/day.

Table 5—Data for annual production estimate of ethanol from bagasse, CLM and molasses.

Cane milled (2003 season)	5 266 000 t
Bagasse produced	1 591 000 t
Dry matter in bagasse	802 000 t
Surplus bagasse possible	431 000 t
Dry matter in surplus bagasse	208 000 t
Additional CLM dry matter	385 000 t
Total dry matter	593 000 t
Cellulose	203 000 t
Hemicellulose	161 000 t
Lignin	142 000 t
Ethanol produced from bagasse & CLM	188.2 ML
Molasses available (2003)	159 000 t
Ethanol produced from molasses	46.4 ML
Total ethanol produced	234.6 ML

Using the NREL figures, making allowance for the lower cost of feedstock, assuming the mill utilities can be used and escalating the capital costs to 2006 figures, a plant investment of about $200 million is anticipated.

Practical implications of a sugarcane biorefinery

There are various synergies that arise from having the plant integrated into the sugar mill. These are:

- Molasses available on site augments the ethanol yield and provides the nutrients for fermentation
- It is not essential that a very high yield of sugars from cellulose and hemicellulose be achieved. The figures in Table 5 show that only about half the lignocellulosic dry matter produced in the mill is used for ethanol production. Unconverted material is routed back to the sugar mill boilers.
- The plant can make use of the utilities available in the mill, including steam and power produced in the grinding season.
- Overhead costs can be saved.
- If no more profitable value can be obtained from lignin, it can be used as a fuel in the sugar mill boilers.

Capital requirements are likely to be extensive for a bagasse hydrolysis/fermentation plant. In addition, changes to infrastructure and equipment to produce, store and process large amounts of sugarcane biomass are likely to be substantial, for year round operation.

The options requiring pretreatment/hydrolysis/fermentation and gasification will not be available for some years; biomass ethanol production has been 5 years away for the last 20 years. The first plants processing biomass are only now being implemented, and on a scale well below the 2 000 t DM/day target suggested.

Conclusions

Sugarcane has vast potential as a viable biomass source for biofuels and energy production. The quantities of bagasse can be doubled if all the leaves and tops are brought to the mill and high biomass yields obtained will be vastly increased with the breeding and development of high biomass or ‘energy’ canes.

The transformation of a sugar mill into a sugarcane biorefinery can take place in stages as various parts of the required technologies are developed. Together with the fact that biomass collection costs are relatively low, this puts sugar mills at an advantage in potential biorefinery development relative to other biomass sources. The economics of lignocellulose production, unlike ethanol from corn or sugarcane juice, are not feedstock cost dependent so much as processing cost dependent.

The most cost-effective processing routes are still being investigated and a major challenge exists in bringing down the cost of biomass processing. New technologies may require subsidies to begin production, but experience in the production of ethanol from corn in the US and from sugarcane in Brazil shows that, once production is started, an on-going reduction in processing costs may be expected. Bio-products other than ethanol may be the key to biorefinery development because they have the potential to provide higher economic value than bulk energy production.

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PERSPECTIVES POUR LA CONVERSION D'UNE USINE SUCRIÈRE EN BIO-RAFFINERIE

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Résumé

LA CONVERSION d'une sucrerie en une unité de transformation de la canne à sucre en de multiples produits, ou bio-raffinerie, présente un fort potentiel pour améliorer la profitabilité de manière durable. Cela implique une sucrerie produisant non seulement le sucre, mais aussi toute une gamme de produits qui améliorera de façon importante ses revenus. En plus des produits à usage direct (par exemple l'éthanol), une bio-raffinerie peut aussi produire une gamme de produits chimiques intermédiaires qui représentent la matière première pour d'autres produits, de la même manière que la production de matières de base chimiques dans une raffinerie pétrolière. Cet article passe en revue les options pour les produits potentiels et les étapes de transformation nécessaires pour la production de ces produits. La matière de base optimale pour une bio-raffinerie pourrait être très différente de la canne à sucre traditionnelle. Elle sera sélectionnée pour sa forte teneur en biomasse plutôt qu'en saccharose, et elle sera possiblement enrichie avec d'autres matières de base agricoles. Les obstacles actuels à la mise en place de projets de bio-raffinerie, qui impliquent le fractionnement et l'hydrolyse des substances ligno-cellulosiques, de même que les traitements thermochimiques sont identifiés. Les économies d'échelle sont en faveur de la mise en place de grandes unités de production pour être viables. Cependant, le choix de certaines options additionnelles, qui dépendent des procédés individuels, permet de convertir une sucrerie en une bio-raffinerie en plusieurs petites étapes moins onéreuses. La mise en place réussie de quelques-uns des procédés de fabrication débattus ici mènerait à une industrie de transformation de la canne plus profitable, diversifiée et développée.

PROSPECTOS PARA CONVERTIR UN CENTRAL AZUCARERO EN UNA BIOREFINERÍA

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Resumen

LA CONVERSIÓN de un central azucarero en una planta procesadora de caña multiproducto ó biorefinería posee un sustantivo potencial para incrementar las ganancias en un modo sostenible. Esto avizora un central azucarero produciendo no solo azúcar sino una gama de productos que mejoran significativamente su corriente de ingresos. Tanto como productos de uso directo (p.e. etanol), una biorefinería puede producir un rango amplio de intermediarios químicos que representan materias primas para otros productos, en modo similar ala producción de compuestos químicos en una refinería de petróleo. El artículo considera la opción de productos potenciales y las etapas de procesos. La materia prima óptima para una biorefinería puede ser significativamente diferente de la caña de azúcar tradicional, procreadas para biomasa y no sacarosa y posiblemente complementada con otras materias primas agrícolas. Se identifican los obstáculos actuales a la implementación de esquemas de biorefinerías que incluyan el fraccionamiento y la hidrólisis de compuestos lignocelulósicos, así como tratamientos termoquímicos. La economía de escala señala hacia la implementación de grandes plantas para alcanzar una viabilidad económica. No obstante, opciones seleccionadas a propósito, dependiendo de la economía de procesos individuales, proveen la ruta para convertir un central azucarero en una biorefinería en un paso más corto y de menor intensidad de capital. La implementación exitosa d algunos de los esquemas de procesamiento que aquí se discuten pueden avizorar una industria procesadora de caña de azúcar más rentable, diversificada y expandida.