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Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China

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Abstract

Reducing the use of non-renewable fossil energy reserves together with improving the environment are two important reasons that drive interest in the use of bioethanol as an automotive fuel. Conversion of sugar and starch to ethanol has been proven at an industrial scale in Brazil and the United States, respectively, and this alcohol has been able to compete with conventional gasoline due to various incentives. In this paper, we examined making ethanol from the sugar extracted from the juice of sweet sorghum and/or from the hemicellulose and cellulose in the residual sorghum bagasse versus selling the sugar from the juice or burning the bagasse to make electricity in four scenarios in the context of North China. In general terms, the production of ethanol from the hemicellulose and cellulose in bagasse was more favorable than burning it to make power, but the relative merits of making ethanol or sugar from the juice was very sensitive to the price of sugar in China. This result was confirmed by both process economics and analysis of opportunity costs. Thus, a flexible plant capable of making both sugar and fuel–ethanol from the juice is recommended. Overall, ethanol production from sorghum bagasse appears very favorable, but other agricultural residues such as corn stover and rice hulls would likely provide a more attractive feedstock for making ethanol in the medium and long term due to their extensive availability in North China and their independence from other markets. Furthermore, the process for residue conversion was based on particular design assumptions, and other technologies could enhance competitiveness while considerations such as perceived risk could impede applications.

Keywords: Energy; Ethanol; Sugar; Sweet sorghum; Economics

1. Introduction

Petroleum provides the single largest fraction of the world's energy, accounting for about 37% of the total world energy used (US DOE, 2002). However, for most countries, much of this petroleum has to be imported, and a large fraction (about 30%) comes from politically volatile locations in the Persian Gulf. Furthermore, petroleum imports are the largest single contributor to trade deficits for many countries. Burning petroleum for power also contributes to a major portion of carbon dioxide emissions to the atmosphere, raising concerns about global climate change. Ultimately, petroleum use is not sustainable, and new sources of energy are needed to address a range of important economic, environmental, and strategic issues and insure a perpetual energy supply.

A large portion of petroleum is used for transportation, and the transportation sector is almost totally dependent on petroleum, particularly for powering personal vehicles and trucks (US DOE, 2002). Furthermore, the transportation sector is rapidly expanding in

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developing countries such as China, straining the supply of petroleum even more. Thus, new sources of sustainable transportation fuels would not only address the problems associated with such a high dependence on petroleum in developed countries but also keep developing countries from facing similar problems.

Ethanol has excellent fuel properties for spark ignition internal combustion engines; for example, its high octane and high heat of vaporization make the alcohol more efficient as a pure fuel than gasoline. Because ethanol is less volatile than gasoline (Bailey, 1996) and has a low photochemical reactivity in the atmosphere, smog formation from evaporative emissions of pure ethanol can be less than for gasoline. Ethanol can also be blended with gasoline to reduce gasoline consumption, improve octane, and promote more complete combustion. However, non ideal interactions with gasoline cause the vapor pressure to increase some for low level ethanol blends (about 10%), but the vapor pressure of the blending gasoline could be reduced to compensate for this effect. Ethanol has a very low toxicity, particularly in comparison to other fuels, and is readily biodegradable in water and soils, reducing penetration of plumes from leaks and consequences of spills compared to petroleum-based fuels.

Extensive experience has been accumulated with using ethanol as a pure fuel and for blending with gasoline (Wyman, 2004). In Brazil, ethanol, mostly from cane sugar, is produced as either anhydrous ethanol that contains 99.6% (vol.) ethanol and 0.4% (vol.) water for use in 20–24% blends with gasoline or as hydrous ethanol containing 95.5% ethanol and 4.5% water that is burned directly as a pure fuel in dedicated ethanol-fueled vehicles. Total Brazilian ethanol production was about 11 200 million litres (3000 million gallons) in 2002 with about 4900 million litres (1300 million gallons) of this total being used as hydrous fuel. In the United States, fuel ethanol production grew from virtually nothing in 1980 to about 8100 million litres (2100 million gallons) by 2002. Almost all of this ethanol is produced from corn starch and is used in 10% ethanol blends. However, special vehicles are also sold in the United States that can burn any fuel containing from 0 to 85% ethanol in gasoline, the latter being designated as E85, with 15% gasoline being used to promote cold starting. Some 48 000 such vehicles were on the road in 2001 consuming about 26.2 million litres (6.9 million gallons) of ethanol. Adding ethanol to diesel fuel results in less particulate emissions, a key need for compression ignition engines, and formulations have been developed to stabilize dispersion of ethanol in diesel fuel. Although most of the experience with ethanol is for spark ignition internal combustion engines, ethanol can achieve high efficiencies and low emissions in fuel cells, but considerable research and development would enhance the readiness of promising but not widely studied ethanol fuel cells.

Although Brazil is the leading producer of fuel ethanol in the world today, ethanol use is growing faster in the United States as MTBE is being phased out due to environmental concerns, and a federal renewable fuels standard (RFS) appears likely that could triple ethanol use at the end of ten years, propelling the United States ahead of Brazil. However, other countries including Canada (around 100 million litres or 26 million gallons in 2002), France (116 million litres or 31 million gallons in 2002, mostly from beet sugar), and Spain (100 million litres or 26 million gallons in 2002 from grain, and an expected output of 325 million litres or 86 million gallons by 2006 which would place the country as the first producer of fuel–ethanol in Europe) also produce ethanol, and the European Commission has the goal of substituting 8% of conventional vehicle fuels with ethanol and biodiesel by 2020 to reduce greenhouse gas emissions. China also planned to introduce about 250 million litres (66 million gallons) of ethanol production capacity from grain in 2001 and seeks to achieve a total annual ethanol production capacity of about 2000 million litres (534 million gallons) within the next few years. India and Thailand are also implementing significant ethanol production and expansion plans (Wyman, 2004).

Most of the immediate expansion in ethanol production in these and other countries is expected to rely on traditional technologies for use of grains (e.g., from corn and wheat) and some sugar (e.g., cane and beet sugar). However, ethanol can be made from very inexpensive and abundant sources of cellulosic biomass including agricultural residues (e.g., corn stover and sugarcane bagasse), forestry wastes (e.g., sawdust and paper sludge), and herbaceous and woody energy crops (e.g., switchgrass and poplar), and these materials insure a supply of inexpensive feedstocks that can extend ethanol production, particularly if large scale use of grains puts upward pressure on grain prices and reduces co-product selling prices. Cellulosic ethanol technology can also be the low cash cost producer of ethanol. However, although substantial improvements have been made in reducing the cost of converting cellulosic biomass to ethanol, the technology has not been proven commercially. In this context, it is important to note that first-of-a-kind facilities have high capital costs and are considered more risky than application of existing technologies, and implementing unproven technology presents serious challenges (Wyman, 1999).

In this study, production of ethanol from sweet sorghum was investigated as a pathway to couple use of new and established technologies for possible application to the growing ethanol market in China. In particular, a scenario was evaluated to ferment the sugar extracted from sorghum to ethanol and also convert the residual sorghum bagasse cellulosic fraction to ethanol while burning the residuals (mostly lignin) for heat and electricity. This approach was compared to traditional methods for extracting sugar for sale or conversion to ethanol and burning the bagasse for heat and power to determine if ethanol production from both fractions offered a potential economic advantage. In addition, another scenario was considered of selling the sugar from sorghum juice and converting the bagasse to ethanol with the residual lignin again burned for heat and power. Cellulosic ethanol technology as described by the National Renewable Energy Laboratory (NREL) was used as the basis for this analysis because of the extensive cost and performance information documented publicly (Wooley et al., 1999a,b), although some changes were made to integrate with sorghum bagasse and different performance parameters than applied by NREL. In addition, we considered how sugar market prices would influence the comparison of these options. We based this analysis on locating the ethanol plant in the Liaoning Province of Northern China to take advantage of data available for that region and account for the variation in feedstock and other operating costs with location.

2. Sweet sorghum in China

Sweet sorghum is a C_4 crop in the grass family belonging to the genus *Sorghum bicolor* L. Moench which also includes grain and fiber sorghum and is characterized by a high photosynthetic efficiency. Sweet sorghum is often considered to be one of the most drought resistant agricultural crops as it has the capability of remaining dormant during the driest periods (Woods, 2000). Like other sorghum types, sweet sorghum probably originated from East Africa and spread to other African regions, Southern Asia, Europe, Australia and the United States. Although a native to the tropics, sweet sorghum is well adapted to temperate climates. The plant grows to a height of from about 120 to above 400 cm, depending on the varieties and growing conditions and can be an annual or short perennial crop. More than 125 sweet sorghum germplasm resources have been registered in China (Lu, 1997). Seeds are typically sown in spring after the rainy season and as soon as the soil temperature remains above 15–18 °C. Seed germination takes place within 24 h in warm and moist soils, and the time to maturity lies between 90 and 120 days. Although the juice, grain and bagasse from sorghum provide opportunities for many uses, most applications around the world are for syrup and forage. An average yield of 1900 L (500 gallons) of syrup per hectare can be achieved, although yields of 800–1200 L (200–300 gallons) per hectare can result if weather conditions are poor. In forage applications, chickens can be fed with seed heads and ruminant livestock can use the grains, leaves and stalks. The organic by-product from sweet sorghum syrup processing is often fed to livestock, left on the field, or composted.

Table 1
Typical characteristics of sweet sorghum varieties[a]

		Varieties			
		Keller	Wray	Rio	Tianza No. 2
Fresh stem yield	[t/ha yr]	49.5	49.8	47.4	52.1
Juice rate	[%]	62.2	65.4	59.0	65.3
Juice sugar degree	[°BX]	19.5	18.5	17.5	16.1
Grain yield	[t/ha]	2.8	1.8	3.4	5.0

[a] Source: UNDP/Shenyang Agricultural University/FAO 1994.

Of the many crops currently being investigated for energy and industry in China, sweet sorghum is one of the most promising, particularly for ethanol production (FAO, 2002; Li, 1997; Grassi et al., 2002). Currently, sorghum production in China (mainly fiber sorghum) is minor compared to corn with about 1 million hectares yielding about 4 millions tons of sorghum compared to 24 millions hectares producing about 100 million tons of corn. Table 1 summarizes typical yields for several varieties of sorghum in the conditions of North China regions. Fiber sorghum in China is used for forage and potable alcohol production. The development of sweet sorghum in China is an agriculture policy option of the government and international agencies that aim at improving agricultural land use by promoting sustainable crops and valuing semi arid and other undeveloped lands. This strategy was strongly advocated since the 1980s with the support of the United Nations Food and Agricultural Organization (FAO), but development of sweet sorghum in China still remains in the demonstration stage. In 1997, the "First International Sweet Sorghum Conference" held in Beijing (Li, 1997) pointed out the multipurpose character of sweet sorghum especially in the context of China.

Research has been undertaken in China to improve the yields of juice and grain from sorghum. Starting in 1983, the Shenyang Agricultural University (SAU) bred new hybrids of sweet sorghum for use as raw material in ethanol production, and grain and sugar production have been improved for Shennong Tianza No. 1, 2 and 3 sweet sorghum hybrid varieties. Shennong Tianza No. 2 is deemed to be the best of these because of its high yields of both grain and fermentables (Table 1). This variety also has a growing period of 140 days and produces 52 t/ha of stems with a 3 m height and 5 t/ha of grains. Alcohol yield from stem and grain are 3500 L/ha and 1680 L/ha, respectively, which are higher than that of most other sweet sorghum varieties.

Recently, with the technical assistance of the FAO, a project was launched in North China (Shandong and Shaanxi Provinces) to develop "sweet sorghum for grain, sugar, feed, fiber and value-added by-products in arid and saline/alkaline regions in China" (Chapman, 2002). In the Shaanxi Province, a pilot plant is under construction to process about 50 tons per year of sweet sorghum stalks and extract about 25 000 L per year of juice and 5000 L of concentrated 70° Brix sugar syrup that can be either sold to the foodstuff industry or fermented to ethanol after dilution. In Beijing, around 20 000 tons per year of sweet sorghum is processed to alcohol and spirits. According to the FAO (Chapman, 2002), growing sweet sorghum for grain and stalks in 2002 provided a yearly gross margin of 1300 US$/ha compared to 27 US$/ha for corn.

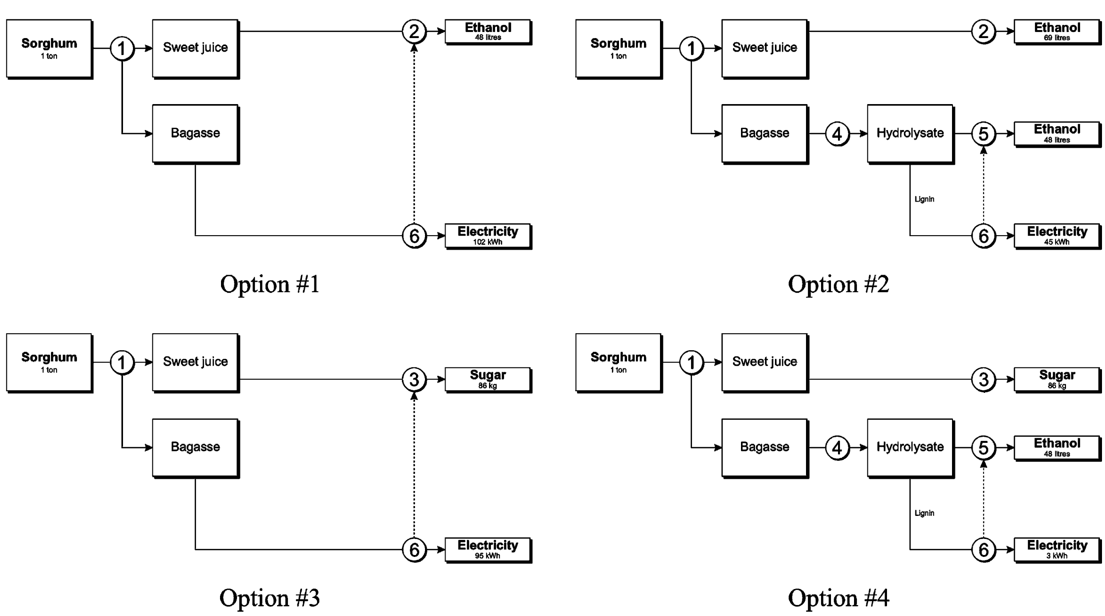
3. Processing of sweet sorghum to sugar versus ethanol

3.1. Options considered

Because of the high sugar content in sweet sorghum, sugar can be readily extracted from the plant and sold on local and world markets. However, due to the lower purity (ratio of the %wt. of sucrose to the %wt. of solubles) of the sugar extracted from sweet sorghum (about 75 apparent purity, AP) compared to that of sugar cane or sugar beet (80–85 AP), it is more costly to produce white sugar from sweet sorghum. Thus, the more likely markets for sorghum sugar will be as syrup for local foodstuffs or as raw material for the food industry. According to the Guangzhou Sugar Cane Industry Research Institute, China, another possible market is brown sugar, which contains molasses. Alternatively, sorghum sugar can be extracted and converted to ethanol. In all cases, the residual plant matter, bagasse, can be burned to provide energy for sugar extraction and recovery, and although more bagasse is produced than needed to provide all the heat and power for sugar extraction, the excess can be burned to produce power for local consumers or for sale to utility customers through the grid. Alternatively, the hemicellulose and cellulose fractions in the bagasse can be hydrolyzed to release their component sugars that in turn can be converted into ethanol, while the residual lignin and other components (not converted to ethanol) can be burned for heat and power. The four options considered in this article are pictured in Fig. 1.

In the first two options, juice is converted to ethanol, whereas in the last two, juice is transformed into white sugar. In options #1 and #3, the bagasse is burned to provide heat (steam) and power to the plant while excess electricity is sold to local utilities. In options #2 and #4, the bagasse is converted to ethanol, while the lignin and other residual solids are burned to provide process heat and power, with excess electricity being sold to local utilities.

The sweet sorghum harvest is limited to about 3–4 months per year to achieve acceptable sugar yields. Fur-



① Juice extraction from sweet sorghum
② Fermentation of C6 sugars/Ethanol recovery (distillation, dehydration)
③ Production of granulated sugar
④ Pre-treatment (dilute acid pre-hydrolysis)
⑤ Simultaneous saccharification and co-fermentation of C6 and C5 sugars/Ethanol recovery
⑥ Co-generation of steam and electricity

Fig. 1. Schematic representation of the various sorghum utilization options considered.

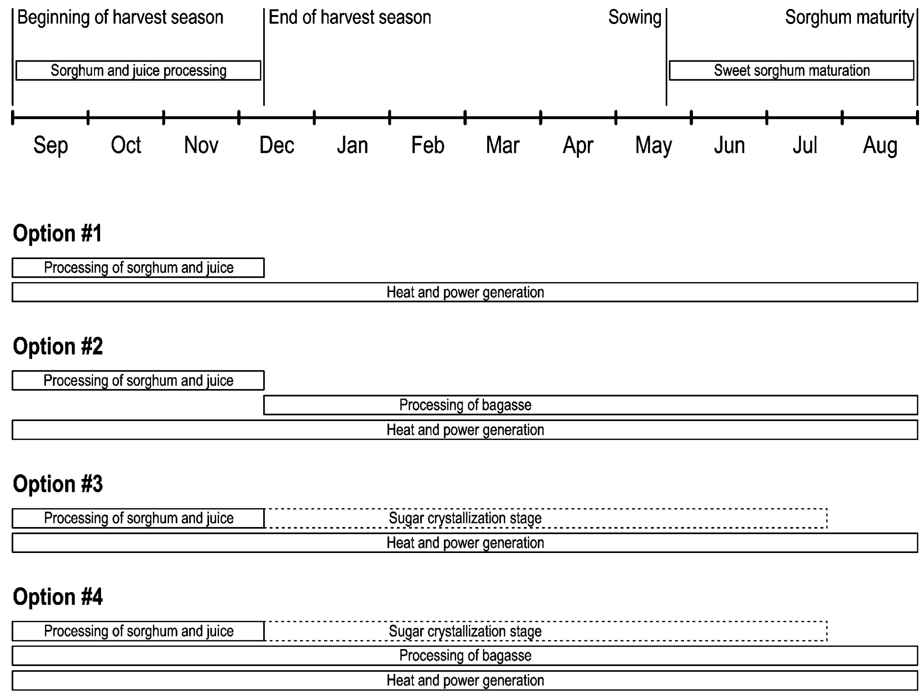


Fig. 2. Time scale and production scheme of the various options.

thermore, the sugar will deteriorate with storage and must be extracted from sweet sorghum soon after the plant is harvested. This situation can be improved in cold climates and it is reported that the stalks may remain stored in the field for 4–5 months as silage (Li, 1997). However, we assume that all of the sugar must be extracted during the harvest season, reducing utilization of capital equipment. Extracted juice cannot be conserved and requires immediate processing. In the case of sweet juice conversion to sugar (options #3 and #4), however, the final stages of crystallization and centrifugation were considered to be performed over 300 days, thereby significantly reducing capital investment for those stages (see Section 3.3). Based on reported experience with sugarcane bagasse, sorghum bagasse is expected to deteriorate slowly, and it should be possible to store this residue for an extended period (Li, 1997). Thus, it is assumed that while sugar extraction systems would be used only for 3–4 months (100 days), bagasse could be stored and processed year round.

The emphasis of this study was on coupling recovery of sweet sorghum sugar for either direct sale or converting the sugar to ethanol with conversion of the residual bagasse to ethanol. On this basis, the process design assumes sweet sorghum is gathered during the harvest season and the sugar extracted soon after the sorghum plant arrives at the processing facility. The sugar is then either converted to ethanol (options #1 and #2) or processed for direct sale (options #3 and #4). The bagasse is either stored in piles for subsequent conversion to ethanol (options #2 and #4) or used immediately to power the juice extraction facility as well as sugar or ethanol production during the sorghum campaign, the excess being stored for power generation during the rest of the year (options #1 and #3). Given these considerations, the production timetable for the four options is shown in Fig. 2.

This study targets consideration of several key issues. Among those, it is important to understand the trade-off between simply recovering the sugars from sorghum for sale and converting these sugars to ethanol, and this decision is expected to be heavily influenced by the selling price for sugar domestically and in world sugar markets. In addition, the ability to utilize the same equipment for processing both bagasse and sugar to ethanol will likely impact the costs of ethanol production.

3.2. Juice extraction

The first processing stage, juice extraction, is common to all the options, and the technology in this article involves mechanical extraction with sugar mill technology, as it is considered that there is sufficient production area around the plant to keep the mill fully supplied during the harvest season. More specifically, the technology considered for juice extraction involves a series of tandem roller mills with countercurrent juice flow to leach solubles (Fig. 3). On this basis, the sugar extraction yield (i.e., the proportion of initial sugars present in the juice after extraction) reaches 87%. Because of the relatively

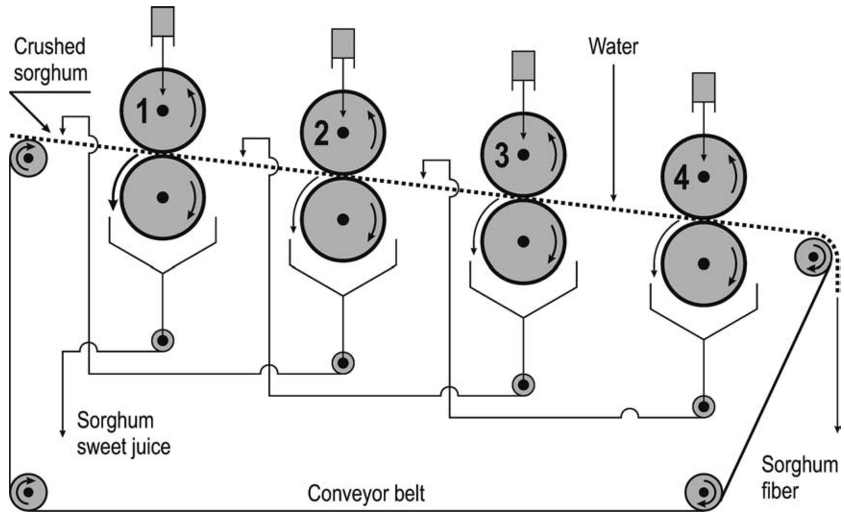


Fig. 3. Schematic diagram of the juice extraction process (adapted from Cundiff et al., 1993).

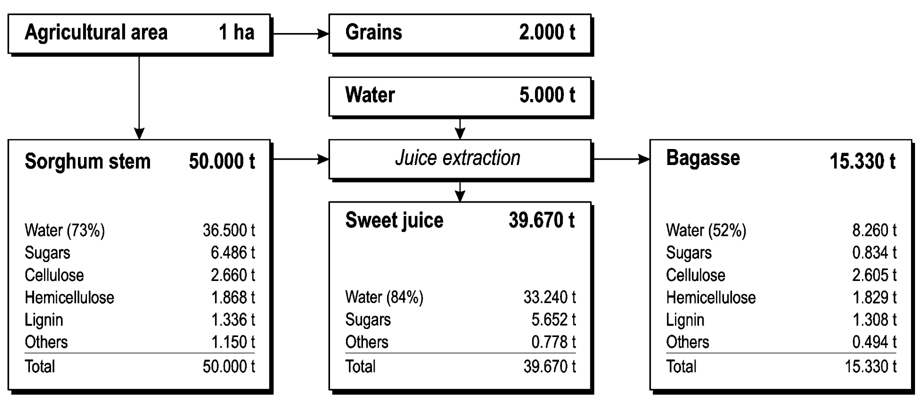


Fig. 4. Mass balance of sweet sorghum juice extraction.

high fiber content in sweet sorghum, it is unlikely that the yield will be as high as from sugarcane (Cundiff and Vaughan, 1987; Cundiff et al., 1993; Woods, 2000). With water and solubles representing about 85% of the total fresh stem weight, the yield of sweet juice (83% wt. water) is about 790 kg per ton of fresh sorghum stems. Fig. 4 illustrates the yields expected from 1 ha of available agricultural land with a high productivity (50 t/ha of fresh matter).

3.3. Juice conversion to sugar

In addition to sugars, the juice contains other compounds and impurities which have to be eliminated before crystalline white sugar can be made. Furthermore, sweet sorghum sugars consist of 85% (wt.) sucrose, 9% glucose and 6% fructose on average, and only sucrose may readily be converted to white sugar (Woods, 2000). The first stage in juice purification is the addition of lime milk (liming) followed by saturation with carbonation gas (mainly carbon dioxide) to precipitate the lime milk in a clarifier and capture the impurities in the raw juice. The lime and carbonation gas are produced in a lime kiln through the decomposition of limestone. The settled solids (mainly calcium carbonate and non-sugars) from the clarifier are filtered in membrane presses and sent to the spent lime storage area, while the clear portion is again saturated in a second carbonation station. The purified juice obtained after the consequent filtration is called thin juice and is thickened in a multi-effect evaporator into thick juice. High pressure steam produced in the boiler house provides the energy for evaporation, and the condensed steam is returned to the boiler house or used as technical water. The evaporated water is used to provide heat to other units in the sugar plant. The thin juice that has been diluted with water during extraction and purification enters the evaporating station with an average sugar content of 15% while the thick juice leaving the evaporators contains approximately 70% sugars. At this stage, the thick juice may actually be partially stored in order to operate the remaining two process steps over a period of 300 days and thereby reduce the investment costs significantly.

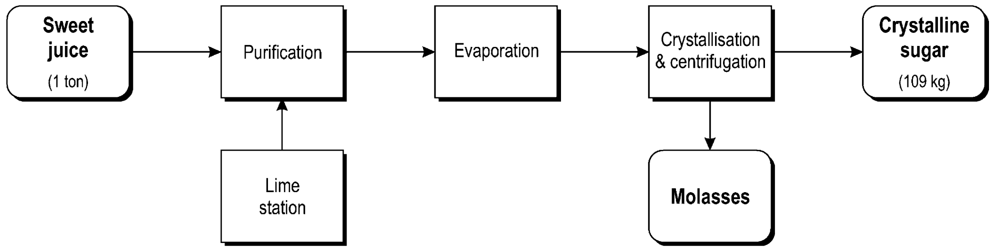


Fig. 5. Block flow diagram for conversion of sweet juice to sugar.

White sugar in its crystalline form is eventually obtained from the thick juice by crystallization in vacuum pans at reduced temperature and pressure. The mixture of crystals (sucrose only) and the mother liquor (green syrup) are separated in centrifuges, where the sugar is washed with hot water. The wet sugar is dried in a drum drier, screened, and finally stored in silos after cooling, while the syrup from the centrifuges is passed through an additional boiling stage to extract most of the remaining sugars (i.e. glucose, fructose and some of the sucrose left). The syrup left over is known as molasses. Although molasses is about 50% sugars, the concentration of non-sugars is so high that no further crystallization is economically possible in a standard processing facility, and molasses are stored in large tanks to be shipped for use by other industries. A simplified flow diagram of the overall process is given in Fig. 5. The sugar yield is 109 kg per ton of sweet juice processed, and the efficiency (expressed as the ratio of the amount of white sugar produced to the initial sugar content) is around 76%.

3.4. Juice conversion to ethanol

The production of ethanol from the sweet juice is a well understood process. It has long been used in Brazil with cane sugar as raw material but also in Europe with beet sugar. The fermentation process envisaged is a continuous cascade using a train of fermentors and a buffer tank. The alcohol concentration rises from 6–7% (vol.) in the first fermentor to 910% (vol.) in the last one. Fermentation temperature is kept between 33 °C and 35 °C.

The growth of yeast is controlled by oxygen supply to the first and second fermentors. Phosphorous (in the form of phosphoric acid) and nitrogen (often from corn steep liquor) are also needed for yeast growth. Yeast cream is separated by centrifuges into holding tanks, and clarified "beer" from the separators is fed into the fermentation buffer tank. Ethanol is then recovered from the fermentation broth (also referred to as "beer") by distillation and dehydration (Fig. 6) for the production of anhydrous ethanol. This is accomplished in two columns, namely a distillation column and a rectification column, coupled with vapor-phase molecular sieves in which a mixture of nearly azeotropic water and ethanol is purified to pure ethanol.

The distillation bottoms stream is concentrated by evaporation using waste heat. The evaporated condensate is returned to the process while the concentrated syrup is combusted in a fluidized bed combustor to make steam for process heat, while excess steam is converted to electricity for use in the plant and for sale to local utilities. Part of the evaporator condensate, along with wastewater, is treated by anaerobic and aerobic digestion. The biogas from the anaerobic digestion is sent to the burner for heat recovery, while treated water is recycled and returned to the process. The ethanol yield is 87 L per ton of sweet juice processed. The efficiency (expressed as the ratio of the amount of ethanol produced to the maximum theoretical ethanol recovery) reaches about 94%.

3.5. Bagasse conversion to ethanol

For this study, conversion of sorghum bagasse to ethanol was based on enzymatic hydrolysis of cellulose and co-fermentation of glucose and xylose to ethanol. This choice was driven by several considerations. First, enzymes offer the possibility of achieving the high yields vital to economic success (Wright, 1988). Second, application of state-of-the-art technology can achieve competitive costs through the use of enzymes (Wyman, 2001). In addition, enzymes appear to offer the greatest prospects for continued improvements that

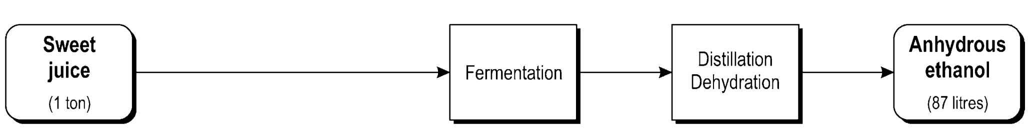


Fig. 6. Block flow diagram for conversion of sweet juice to ethanol.

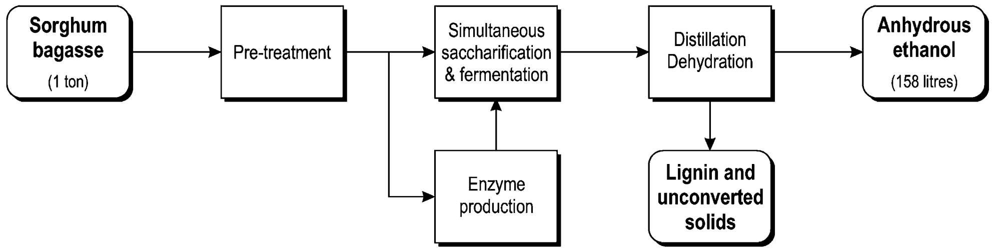


Fig. 7. Block flow diagram for conversion of sorghum bagasse to ethanol.

could make even lower costs possible (Lynd et al., 1996). Finally, the National Renewable Energy Laboratory (NREL) has documented extensive performance and cost information (Wooley et al., 1999a,b), and even though other performance and designs are feasible, the NREL information provides a convenient platform from which to evaluate enzymatic routes. Thus, the technology described here (Fig. 7) is based on that configuration although other technologies for pretreatment and other operations could be substituted if desired.

Because the overall enzymatic route is well described elsewhere, the reader is referred to these sources for more detailed information (Wooley et al., 1999a,b; Wyman, 2001; Knauf and Moniruzzaman, 2004). In more general terms, the process begins with the pretreatment step in which the material is held for around 10 min at about 160–190 °C with 0.5–1.0% dilute sulfuric acid to catalyze hemicellulose removal by hydrolysis and expose the cellulose for saccharification by enzymes with high yields. Acid hydrolysis of hemicellulose realizes good yields of sugars from hemicellulose during pretreatment, and acid costs are relatively low. During this operation, the five different sugars in hemicellulose—arabinose, galactose, glucose, mannose, and xylose–together with other constituents in bagasse such as acetic acid are released. The pretreated material then passes to a vessel with a sudden drop in pressure to rapidly lower the temperature and stop the reaction. This flash operation also removes some of the acetic acid, furfural, and other fermentation inhibitors that are either released from the biomass or produced by degradation reactions during pretreatment. Next, the liquid is removed from the remaining solid fraction that contains most of the cellulose and lignin and pumped to an ion exchange operation to remove a portion of acetic and virtually all of the sulfuric acid. The liquid is neutralized with lime, and additional lime is added to increase the pH to about 10 to remove toxics to downstream biological steps in an operation known as ''overliming'' (Fig. 8). One should note, however, that the ion exchange step was removed in NREL's latest process design (Aden et al., 2002) where it is considered that overliming is enough to remove most of the toxics for downstream stages. The treated liquid is then mixed back with the solids before the fermentation.

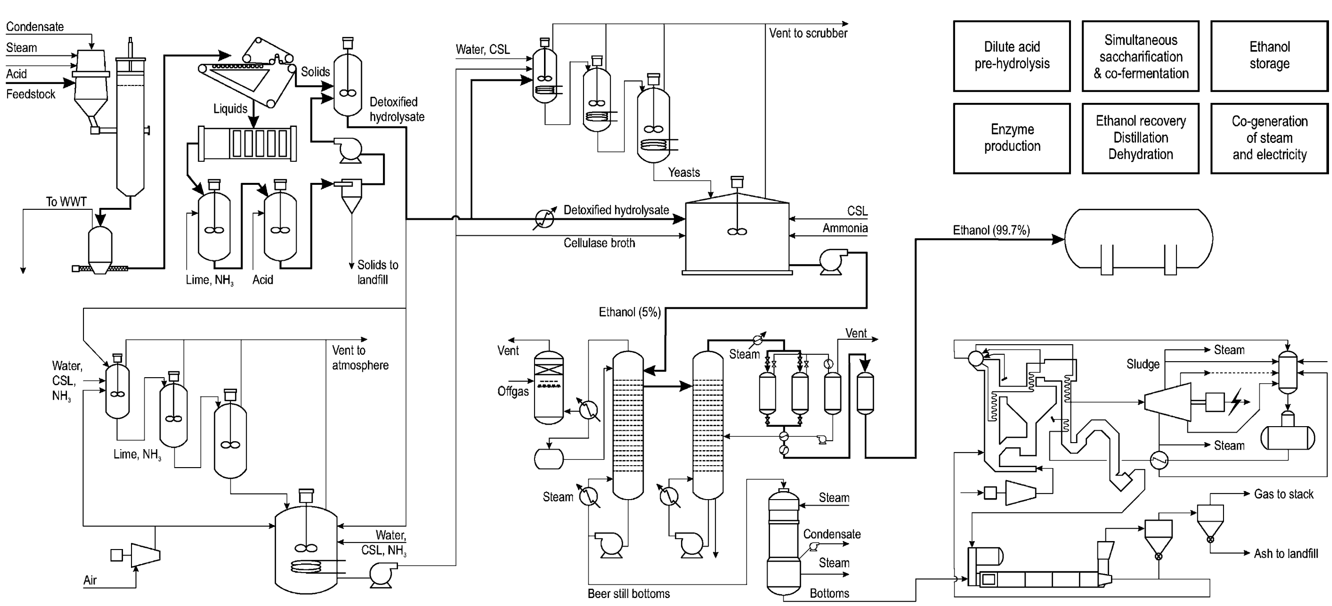


Fig. 8. Schematic representation of the NREL process for ethanol production.

A small portion of the solids and the treated liquid is fed to a batch operation to produce cellulase enzyme by the fungus *Trichoderma reesei*, and the entire effluent from cellulase production plus the bulk of the pretreated solids not used for making enzymes are added to a fermentor to release glucose from cellulose. In addition, the conditioned liquid hydrolyzate is also added to the same vessel along with an organism that ferments the sugars from hemicellulose plus the glucose released from cellulose to ethanol. In this operation, referred to as SSCF for simultaneous saccharification and co-fermentation, the glucose and cellobiose released from cellulose during enzymatic hydrolysis are quickly converted to ethanol, keeping the concentration of both of these powerful inhibitors of cellulase activity low. It has been shown that this approach improves the rates, yields, and concentrations for ethanol production compared to performing the hydrolysis and fermentation steps sequentially even though lower temperatures are required than are optimum for hydrolysis to accommodate the less tolerant fermentation micro-organisms (Spindler et al., 1991). In addition, the presence of ethanol impedes successful invasion by contaminating organisms, and only a single set of fermentors are required for SSCF compared to the three sets that would be used if saccharification, hemicellulose sugar fermentation, and cellulose sugar fermentation were done separately, thereby reducing the overall cost (Wright et al., 1988).

The fermented beer containing about 5% (vol.) ethanol passes on to distillation where it is concentrated to approximately 95% ethanol in the overhead. Molecular sieves then follow to recover the nearly 100% ethanol product, suitable for blending with gasoline or use as a pure anhydrous fuel. The solids, containing mostly lignin and solubles from distillation are concentrated and burned to generate steam that can provide all of the heat and electricity for the process with some excess electricity left to export. Water is treated by anaerobic digestion, and the resulting biogas is burned for steam generation.

The ethanol yield is 158 L per ton of sorghum bagasse. The efficiency (expressed as the ratio of the amount of ethanol produced to the maximum theoretical ethanol recovery) reaches 80%. As suggested by NREL (Wooley et al., 1999a,b), it was assumed in the calculations that no sugars other than glucose and xylose were fermented to ethanol. Conversion data used in the calculations were those quoted by NREL in their first lignocellulosic biomass to ethanol process design (Wooley et al., 1999a,b). In its latest process design, however, NREL reported improved conversion yields in a scenario for the horizon 2010 (Aden et al., 2002), with such improvement representing a 15% increase in ethanol yields, for the same amount of processed biomass. Both sets of performance factors are summarized in Table 2.

Table 2
Chemical reactions conversion factors as reported by NREL

Feedstock	First process design yellow poplar	2010 scenario corn stover
Conversion yields		
Cellulose to glucose	0.80	0.90
Xylan[a] to xylose	0.75	0.90
Glucose to ethanol	0.92	0.95
Xylose to ethanol	0.85	0.85
Mannan to mannose	0.75	0.90
Mannose to ethanol	–	0.85
Arabinan to arabinose	0.75	0.90
Arabinose to ethanol	–	0.85
Galactan to galactose	0.75	0.90
Galactose to ethanol	–	0.85
Ethanol yield [l/t bagasse]	117	143

[a] Xylan, arabinan, mannan and galactan are polymers of xylose (C5), arabinose (C5), mannose (C6) and galactose (C6) respectively. These polymers together constitute what is commonly referred to as hemicellulose.

3.6. Process design approach

The process model followed closely the NREL design as reported so thoroughly by them (Wooley et al., 1999a,b). A spreadsheet was developed to calculate all material and energy balances based on specified yields, and operating costs were calculated based on these flow and energy use rates coupled with available cost information. Then, appropriate rates were used to size equipment, and equipment costs were calculated based on the NREL information for all of the steps from feedstock handling and storage to manufacture of ethanol. The power law scale factors reported by NREL were used to estimate the change in cost of each equipment item with varying feedstock composition, cellulosic feed rate, yields, and other information. The installation factors reported by NREL were used to estimate the cost of installed equipment, and their cost factors were applied to estimate the total cost of capital including warehousing, engineering profit, and so forth. Finally, the construction time, startup schedule, capacity utilization factors, capital recovery approach, and other factors per NREL were applied to estimate the unit capital cost to achieve a target rate of return for equity financing. The spreadsheet was run initially at NREL conditions to insure that they were correct and could duplicate the NREL results. Changes were subsequently made in various parameters to reflect the composition of sorghum bagasse, yields selected for the process, and any other changes, as noted later.

4. Economics of refining sorghum to ethanol and sugar

The four options described in the previous paragraphs were compared in terms of their net present value

(NPV) over a period of 20 years, the assumed economic lifetime of the installations. In each case, annual operating cash receipts included sales of ethanol and/or sugar, excess electricity, and by-products (e.g., molasses). Annual operating cash payments were divided into fixed operating costs (salaries, general overhead, insurance and taxes and maintenance) and variable operating costs (purchase of raw materials). For each option, the total project investment (TPI) was calculated from the total equipment cost (TEC), according to the following model (example given for a TEC of 100 million US$), adapted from NREL to Chinese conditions:

Total equipment cost (TEC)	100 000 000	US$
Warehouse [1% of TEC]	1 000 000	US$
Site development [4% of TEC]	4 000 000	US$
Total installed cost (TIC)	105 000 000	US$
Field expenses [12% of TIC]	12 600 000	US$
Home office & construction fees [15% of TIC]	15 750 000	US$
Project contingency [3% of TIC]	3 150 000	US$
Total capital investment (TCI)	136 500 000	US$
Other costs (startup, permits, etc.) [10% of TCI]	13 650 000	US$
Total project investment (TPI)	150 150 000	US$

As described in the example above, total additional investment costs represent around 50% of the TEC. As mentioned before, TEC for the ethanol plant was derived from NREL data according the composition of the substrate and treatment capacity (specific to each option), using the spreadsheet developed at the Laboratory of Energy Systems (LASEN) of the Swiss Federal Institute of Technology of Lausanne (EPFL). TEC for the sugar plant and the extraction unit were adapted from various Chinese sources to match the treatment capacity. Like for investment costs, operating costs were calculated using the spreadsheet in accordance with the composition of the feedstock (juice or bagasse) and the capacity.

For all the options developed in this article, the reference year (i.e. the year when production is supposed to start) was considered to be 2005. The calculations for the NPV are performed over the period 2005–2025. During the start-up period which was set as 1 year, variable operating costs as well as cash receipts were reduced by a factor of 2 with respect to full-capacity expectations, while fixed operating costs were maintained. The various plant options were designed for a treatment capacity of 2 million tons of sweet sorghum. Juice extraction is performed over a period of 100 days, resulting in a feedrate of about 870 t/h. Given the juice and bagasse yields indicated on Fig. 4, the treatment capacities of the various units are presented in Table 3, for each option. The price of sweet sorghum stalks was taken as 18.1 US$/t (fresh matter), while the prices of purchased gas and electricity were taken as 220 US$/t and 6.0 US¢/kWh respectively. Excess electricity was considered to be sold to the grid at 3.6 US¢/kWh (close to the Chinese average production cost). Finally, the price of molasses (about 70% dry matter and 50% sugar) was set at 140 US$/t.

4.1. Results

The results of the economic study of the four various processing schemes of sweet sorghum are presented in Table 4 with all monetary data given in US currency (US$). For each of the four options considered, the

Table 3
Treatment capacities of the different units within the four options

Substrate	Extraction	Ethanol plant		Sugar plant
	Sorghum	Juice	Bagasse	Juice
Option #1	2 000 000 t/yr 870 t/h 100 days	1 586 800 t/yr 690 t/h 100 days	– – –	– – –
Option #2	2 000 000 t/yr 870 t/h 100 days	1 586 800 t/yr 690 t/h 100 days	613 200 t/yr 100 t/h 265 days	– – –
Option #3	2 000 000 t/yr 870 t/h 100 days	– – –	– – –	1 586 800 t/yr 690 t/h 100 (300[a]) days
Option #4	2 000 000 t/yr 870 t/h 100 days	– – –	613 200 t/yr 72 t/h 365 days	1 586 800 t/yr 190 t/h 100 (300) days

[a] The number of days in brackets indicates the number of operating days per year for the crystallization and centrifugations stages of the sugar production process.

Table 4
Summary table of the economics of the four options considered

Annual expenses	Unit cost	Option #1		Option #2		Option #3		Option #4	
		Quantity	Annual costs	Quantity	Annual costs	Quantity	Annual costs	Quantity	Annual costs
Investment costs									
Equipment costs			15.3 M$/yr		19.4 M$/yr		20.6 M$/yr		24.9 M$/yr
Additional costs			7.1 M$/yr		9.2 M$/yr		9.7 M$/yr		12.0 M$/yr
Total			22.4 M$/yr		28.6 M$/yr		30.3 M$/yr		33.9 M$/yr
Variable op. costs									
Feedstock	18.100$/t	2000 kt/yr	36.2 M$/yr	2000 kt/yr	36.1 M$/yr	2000 kt/yr	36.2 M$/yr	2000 kt/yr	36.1 M$/yr
Raw materials	–	–	1.5 M$/yr	–	5.0 M$/yr	–	1.8 M$/yr	–	5.1 M$/yr
Electricity	0.060 $/kWh	0.0 GWh/yr	0.0 M$/yr	0.0 GWh/yr	0.0 M$/yr	0.0 GWh/yr	0.0 M$/yr	0.0 GWh/yr	0.0 M$/yr
Natural gas	220.000 $/t	0.0 kt/yr	0.0 M$/yr	17.0 kt/yr	7.6 M$/yr	0.0 kt/yr	0.0 M$/yr	8.0 kt/yr	3.5 M$/yr
Total			37.7 M$/yr		48.7 M$/yr		38.0. M$/yr		44.7 M$/yr
Fixed op. costs									
Salaries, general OHs			0.4 M$/yr		0.6 M$/yr		0.4 M$/yr		0.7 M$/yr
Maintenance			3.0 M$/yr		3.8 M$/yr		4.1 M$/yr		4.9 M$/yr
Insurance & taxes			2.3 M$/yr		3.0 M$/yr		3.1 M$/yr		3.8 M$/yr
Total			5.7 M$/yr		7.4 M$/yr		7.6 M$/yr		9.4 M$/yr
Total annual expenses			65.8 M$/yr		84.7 M$/yr		75.9 M$/yr		91.0 M$/yr
Annual revenues									
Ethanol	0.430 $/l	137.8 Ml/yr	59.7 M$/yr	234.7 Ml/yr	101.8 M$/yr	0.0 Ml/yr	0.0 M$/yr	96.9 Ml/yr	42.0 M$/yr
Sugar	360.000 $/t	0.0 kt/yr	0.0 M$/yr	0.0 kt/yr	0.0 M$/yr	172.4 kt/yr	62.2 M$/yr	172.4 kt/yr	62.2 M$/yr
Electricity	0.036 S/kWh	203.9 GWh/yr	7.4 M$/yr	89.5 GWh/yr	3.2 M$/yr	189.1 GWh/yr	6.8 M$/yr	5.5 GWh/yr	0.2 M$/yr
Molasses	140.000 $/t	0.0 kt/yr	0.0 M$/yr	0.0 kt/yr	0.0 M$/yr	87.8 kt/yr	12.7 M$/yr	87.8 kt/yr	12.7 M$/yr
Total annual revenues			67.1 M$/yr		105.0 M$/yr		81.7 M$/yr		117.1 M$/yr
Energy consumption									
Electricity consumed			106. 8 GWh/yr		168.4 GWh/yr		97.4 GWh/yr		157.5 GWh/yr
Steam consumed			458.1 GWh/yr		830.8 GWh/yr		268.0 GWh/yr		603.6 GWh/yr

following information is reported: (1) annual investment costs (in M$/yr), (2) annual variable operating costs (in M$/yr), including feedstock, raw materials and energy costs, (3) annual fixed operating costs (in M$/yr), including salaries, general overheads, maintenance, insurance and taxes (4) annual revenues (in M$/yr), including sales of ethanol, sugar, and by-products (i.e. excess electricity and molasses) and (5) consumption of electricity and steam (in GWh/yr).

The respective economic merits of each option were then compared based on the net present value (NPV), the internal rate of return (IRR) and the pay-back period. The IRR corresponds to the discount rate that gives a zero NPV and in general terms provides a measure of the return on investment for each project. An IRR smaller than the discount rate, corresponds to a negative NPV and would not meet investors' return criteria. Furthermore, investors would favor investing in those projects with the greatest IRR assuming that all options have the same risk. The pay-back period, based on the period required for the project to repay the investment outlay, is yet an alternative indicator of investment return, and is also widely used in practice. As opposed to the NPV and the IRR, however, it does not use the discounting technique. The results are presented in Table 5.

The NPV turns out to be positive for all the options considered, indicating that, in the conditions described in this article, all should represent a profitable business. From an economic point of view, converting the bagasse to fuel–ethanol seems to be a better choice than burning it for heat and power production, regardless of what is done with the juice. The NPV approach places option #4 (converting the juice to sugar and the bagasse to ethanol) as the best option, but the IRR and the payback period approaches tend to favor option #2 (converting both the juice and the bagasse to ethanol) slightly. As these indicators are dependent on the choice of parameters such as the discount rate and the prices of sorghum, sugar, ethanol and excess electricity, a sensitivity analysis was performed in order to evaluate how changes in these parameters affected the net present value of each option.

4.2. Sensitivity analysis

The initial values of the discount rate and prices of sweet sorghum. ethanol, sugar, and excess electricity were set to 8%, 18.1 US$/t, 0.43 US$/l360 US$/t, and 3.6 US¢/kWh, respectively. The results of the sensitivity analysis are summarized in Fig. 9. Over a range of discount rates from 5 to 10% shown in Fig. 9a, it appears somewhat preferable to convert the bagasse to ethanol for sale at 0.43 US$/l than to burn it for heat and power with excess electricity being sold at 3.6 US¢/kWh. Regardless of what is done with the bagasse, producing sugar sold at 360 US$/t is more attractive than processing the juice to alcohol for sale at 0.43 US$/l over the whole range of discount rates envisaged in the present analysis.. The internal rate of return (IRR) can be read from the same graph for options #1 and #3.

As indicated on Fig. 9b, all the options are particularly sensitive to the price of biomass. For instance, an increase of 4% (resp. 16%) in the price of biomass gives option #1 (resp. option #3) a zero NPV. Options #2 and #4, however, will still show a positive NPV, as long as the price of biomass does not increase by 56% and 72% respectively. Varying the price of biomass does not affect the relative merit of the four options.

The effect of the selling price of excess electricity on the NPV was also determined over a range of 1.0–6.0 US¢/kWh. As there is almost no excess electricity generated for option #4, it can be seen in Fig. 9c that the NPV for this option is relatively insensitive to varying the price of excess electricity. Within the range considered, it appears that it is always more profitable to convert the bagasse to ethanol than to burn it for heat and power, one reason being that, with a moisture content of about 50%, the bagasse does not make a very efficient fuel for power generation, whereas it makes an ideal feedstock for fuel–ethanol production. Options #1 and #3, however, could show a negative NPV when the selling price of excess electricity goes below 3.4 US¢/kWh and 1.2 US¢/kWh, respectively. Again, within the range of excess electricity prices considered, the ranking of the options remains the same.

The price of fuel–ethanol in China is currently around 0.43 US$/l, the default value in this analysis. It can be deduced from Fig. 9d that the NPVs of options #1, #2, and #4 become negative when the price of ethanol goes below 0.42 US$/l, 0.35 US$/l, and 0.20 US$/l, respectively. Option #3 is not affected by the price of ethanol. Overall, the results suggest that, whether the bagasse is burned for heat and power or converted to ethanol, producing sugar is more profitable than processing juice to ethanol as long as the selling price of ethanol remains below 0.46 US$/l. In other words, only a few percent increase of the market price of ethanol (with respect to the default value of 0.43 US$/l) would give option #1 (resp. option #2) a higher NPV than option #3 (resp. option #4).

The current price of white sugar in China is around 360 US$/t, the default value for this study, although this price fluctuates considerably. However, the Chinese

Table 5
NPV, IRR and pay-back period of the four options

Options	NPV [M$]	IRR [%]	Pay-back period [yrs]
Option #1	4.4	8.3	8.9
Option #2	169.7	015.2	5.3
Option #3	40.3	09.8	7.9
Option #4	208.7	014.8	5.5

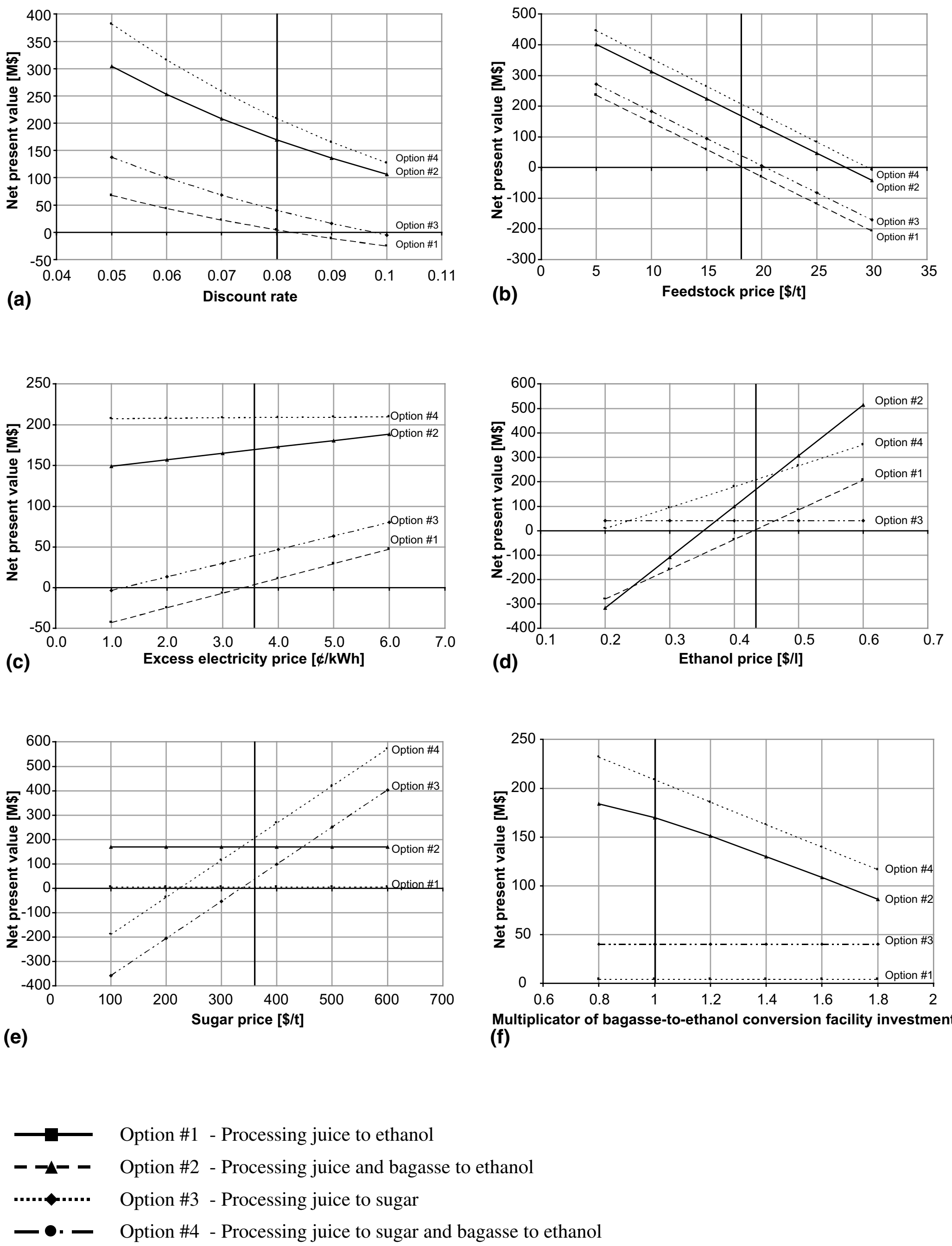


Fig. 9. Results of the sensitivity analysis. (a) varying discount rate, (b) varying biomass price, (c) varying excess electricity price, (d) varying ethanol price, (e) varying sugar price, (f) varying bagasse-to-ethanol investment cost.

sugar market seems particularly protected, as the price of sugar on the international market is around 200–250 US$/t. Furthermore, the forecasts for 2005 (F.O. Lichts, 2004) give a price of sugar on the world market around 200 US$/t, at which conditions neither option #3 nor option #4 would be economically viable. The results in Fig. 9e show that only a 10% decrease of the sugar market price would make juice-to-ethanol more profitable than juice-to-sugar, i.e. would give option #1 (resp. option #2) a higher NPV than option #3 (resp. option #4), processing juice to sugar. Overall, these results suggest that the profitability of options #3 and #4 is very sensitive to the price of sugar, an effect compounded by the high volatility of the Chinese sugar market that has reached prices as high as 440 US$/t and as low as 165 US$/t over the past few years.

In the conditions envisaged in the present article, the two options where the bagasse is converted to ethanol (options #2 and #4) give the highest NPVs. However, it is worth mentioning that, although the conversion of lignocellulosic biomass (e.g. bagasse) to ethanol should soon reach commercialization (source: US DoE Biomass Program), it has not yet been proven at an industrial scale and indeed still features a relatively high business risk due to the uncertainty around the conversion process itself. In order to explicitly take this business risk into account in the present economic analysis, the sensitivity of the NPV of options #2 and #4 with respect to the investment cost of the bagasse-to-ethanol process was analyzed (Fig. 9f). For both options #2 and #4, a 50% increase of the investment cost of the bagasse-to-ethanol process results in a 30% reduction of the NPV. In the range considered (up to a doubling of the specific investment cost of the process), the two options remain largely profitable and better choices compared to options #1 and #3. Although the relative merit of each option would remain the same, the profitability of these two options is indeed sensitive to such a parameter.

Finally, the sensitivity of the NPV of the various options with respect to the size of the plant was analyzed. The results for this analysis are given in Fig. 10, the size of the plant being represented by the sorghum treatment capacity. Although varying the treatment capacity does not change the ranking of the four options, it allows determination of the critical size for each option. The variation range considered is from 1 Mt to 3.5 Mt of sorghum treated per year, with 2 Mt/yr being the default value and also the critical size for option #1. Fig. 10 shows that the critical size for option #3 is around 1.4 Mt/yr, whereas that for options #2 and #4 is below 1 Mt/yr. More generally, increasing (resp. reducing) the treatment capacity increases (resp. reduces) the gap (in terms of NPV) between the various options.

Overall, the sensitivity analysis shows that it is difficult to clearly rank the four options presented in this article, as the "economic performance" of each option depends on a set of many independent parameters such as the discount rate or investment costs and the prices of sorghum, ethanol, sugar, and excess electricity sold to the grid. In addition, the economics of the various options are very sensitive to cost and performance parameters for the technologies considered, and better cost and performance are possible than for the process parameters employed. For example, as mentioned earlier, improving the ethanol yield by 15% from lignocellulosic biomass and the use of optimized micro-organisms could lower the production cost of ethanol and possibly improve the NPV of options #2 and #4 to 225.4 M$ and 264.5 M$ respectively. In addition, the ion exchange unit is likely not needed, as suggested earlier. Thus, the outcome will vary with the exact technology employed, and the relative merit of these options is likely to change with different choices of biomass-to-ethanol technologies, yields from key process steps, electricity production choices, and other process aspects. In addition, the approach to integrating sugar, ethanol, and power production can have important consequences on capital utilization and costs. As a result, it is vital to more accurately estimate the costs and performance of technologies for a specific application to this market, and a close study of the local market and opportunity costs is essential to judge their relative economic merit. An alternative to the NPV approach described so far, indeed, is the opportunity cost approach, the principles of which are presented in the next section.

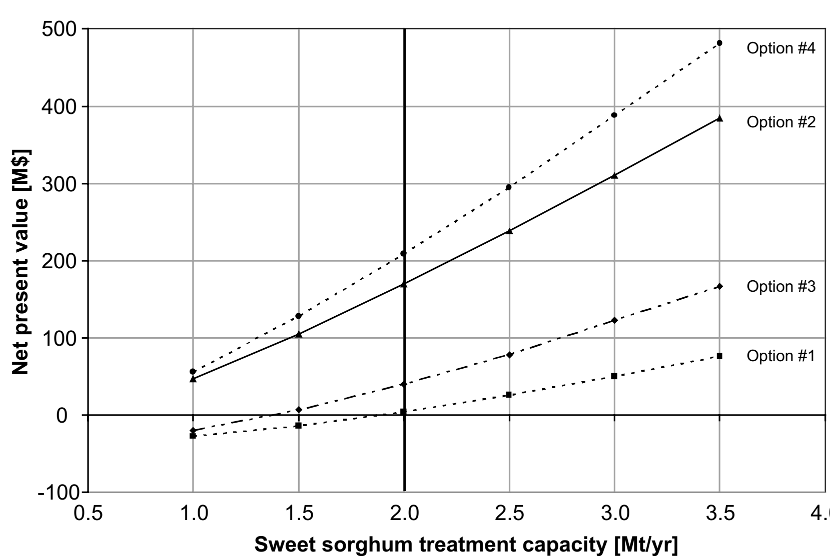


Fig. 10. Sensitivity of the NPV with respect to the sorghum treatment capacity.

5. Opportunity cost approach

An opportunity cost approach was developed to independently assess the relative merit of the various options for processing sweet juice on the one hand and cellulose and hemicellulose on the other hand. Two possible options were considered for processing sweet juice, namely conversion to sugar and conversion to ethanol, and cellulose and hemicellulose were either converted to ethanol or burned for heat and power. The possible combinations of these options gave rise to the four options considered.

As opposed to the NPV approach which considered the entire installation as a whole (including the extraction and processing of the juice as well as the processing of the bagasse), the opportunity cost approach envisaged in this section focused on a single process with the aim of answering the question: "which is the best opportunity among a given set of options for making a given product?"

5.1. The case of sweet juice

The choice among options can be seen from two different perspectives, as illustrated here for the case of sweet juice. From the point of view of an investor who could buy sweet juice at a given price, say 30 US$/t, which option between converting the juice to fuel–ethanol or sugar would bring him the largest profit? The question can also be addressed from the point of view of a sweet sorghum processor whose business would be limited to the extraction of juice from the sorghum plant by estimating whether the best potential client would be a fuel–ethanol producer or a sugar producer. In other words, which of the two potential clients could afford the highest price for the juice? This last statement actually gives the definition of the opportunity cost, in this case, for sweet juice.

A straightforward argument could be made as follows: 1 ton of sorghum sweet juice would yield about 87 L of fuel–ethanol (i.e. 37.40 US$ at 0.43 US$/l) or 109 kg of sugar (i.e. 39.20 US$ at 360 US$/t) plus 56 kg of molasses (i.e. 7.80 US$ at 140 US$/t), and therefore, it is more profitable to transform the juice into sugar rather than into ethanol. This approach, however, does not take into account the cost of processing the juice and could also be misleading in some cases, as it considers only revenue rather than net benefit.

The approach we envisage here takes into account the cost of transforming the raw material into the finished product in addition to the selling price of the latter. Given the selling price of the end-product (ethanol or sugar, in this case), the present analysis aims at evaluating the "shadow price" (in other words, the "maximum allowable cost") of the input (sweet juice, in this case), by taking into consideration the processing cost. The conversion chain which gives the highest "shadow price" determines the "value" (in other words, the "maximum selling price") of the input and hence the most preferred customer (from the point of view of the producer of sweet juice). The flow diagrams on Fig. 11 provide an example for the case of sweet juice conversion to sugar or ethanol.

In case (a), the "shadow price" of sweet juice is equal to the income due to ethanol sales (59 760 000 US$/yr) minus the cost of processing the juice to ethanol (17 110 000 US$/yr) divided by the mass of juice processed per year, that is 26.90 US$/t. Similarly, in case (b), the shadow price of sweet juice is equal to the income due to sales of sugar and molasses (74 870 000 US$/yr) minus the processing cost (29 150 000 US$/yr) divided by the amount of juice processed, that is 28.80 US$/t. The processing cost, in each case, includes annual capital recovery costs as well as fixed and variable annual operating costs. As the process of converting the juice to sugar or ethanol has been mentally separated from the extraction process and the production of heat and power, all the costs specifically associated to these units were not taken into account. Prices were however attributed to steam (1.8 US¢/kWh$_{th}$) and electricity (3.6 US¢/kWh$_e$) and charged to the two alternative processes (i.e. juice to ethanol and juice to sugar), according to the respective uses of heat and power. In other words, the steam and the electricity were considered to be supplied by an independent power producer using sweet sorghum bagasse as a fuel.

The "opportunity cost" is here defined as the "shadow price" of a particular product for a given application minus the "shadow price" of that same product for a different application. This difference therefore reflects how much income is gained or sacrificed by using the product in an application versus another.

This approach as illustrated by Fig. 11 leads to the conclusion that producing sugar as opposed to producing ethanol from sweet juice is more profitable, as the process results in a higher shadow price. In other words, a sugar producer could afford to pay a higher price for sweet juice than an ethanol producer. Likewise, the juice extraction unit operator could hope to realize higher revenues by selling the juice to a sugar producer than to an ethanol producer. Therefore, the "value" of sweet juice (i.e. the "maximum selling price" of sweet juice from the point of view of the juice producer) is 28.80 US$/t.

Although this analysis is actually in accordance with the results presented in Section 4 (Table 5) of this article—in the sense that option #3 indicates a higher net present value (NPV) than option #1—it is not actually possible to make a parallel between the two approaches, as the NPV analysis considers the whole system including extraction as well as heat and power production whereas the opportunity cost approach isolates somehow the

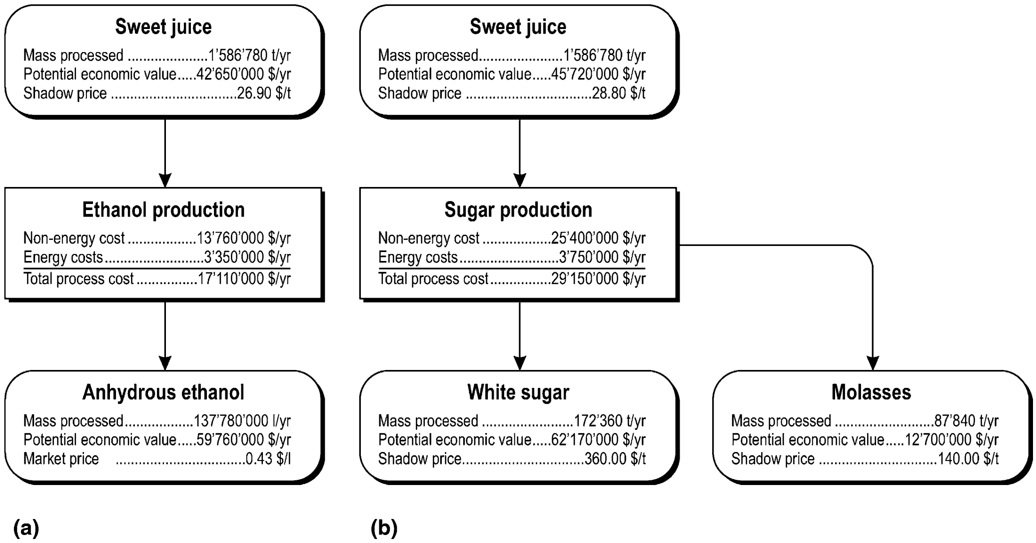


Fig. 11. Calculation of the "shadow price" of sweet juice through option #1 (a) and option #3 (b).

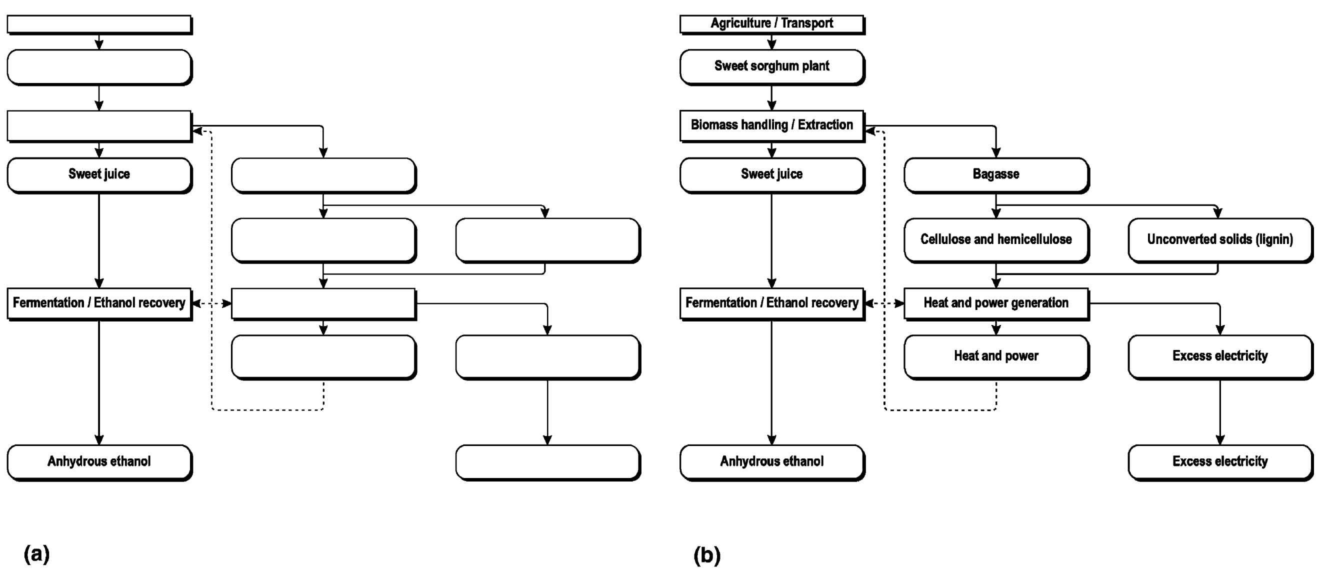


Fig. 12. Definition of the systems in the opportunity cost approach (a) and the NPV approach (b).

producers of ethanol and sugar respectively (Fig. 12). The unbundling of the various systems in the more general opportunity cost approach therefore creates an offset which prevents from drawing an analogy with the more specific NPV approach. For instance, the prices of steam and electricity are fixed in the opportunity cost approach, whereas they are not apparent in the NPV approach as heat and power are produced internally (i.e. within the system). The NPV approach considers implicit cross-subsidies between the various units of the global system, in the sense that it evaluates the economic merit of the system as a whole rather than that of each unit separately. This is not the case in the opportunity cost approach.

This opportunity cost analysis offers the possibility to evaluate the improvement in ethanol yield from sweet juice which would make option #1 (converting the juice to ethanol) more profitable than option #3 (converting the juice to sugar). Indeed, a 5.1% improvement of ethanol yield from sweet juice would produce 146 million litres of ethanol per year (i.e. 62 830 000 US$/yr), and in turn make the shadow price of the juice equal to that obtained with option #3 (i.e. 28.80 US$/t). Similarly, one could evaluate the processing cost reduction necessary to make fuel–ethanol production competitive with sugar production in terms of the shadow price of sweet juice, and an 18% reduction of ethanol non-feedstock production cost would achieve such an objective.

Just like in the NPV approach, the calculated shadow prices are strongly dependent on the prices considered for ethanol, sugar, and energy in the form of steam or electricity. In the conditions described in this article, for instance, a drop of only 5% in the price of sugar would make the shadow price of sweet juice equal in options #1 and #3.

The shadow price of sweet juice was also calculated for option #2, by considering that ethanol from juice and ethanol from bagasse were produced by two distinct businesses sharing the common equipment for the two processes and therefore the cost of that equipment. This last case results in a shadow price of 29.40 US$ per ton of juice, which is actually higher than that obtained for option #3. This statement leads to the conclusion that converting sweet juice to ethanol may represent the best option for an investor only if investment costs can be shared with another local ethanol producer who would operate his plant at a different period of the year. On the contrary, if investment costs have to be assumed entirely by the investor, converting the juice to sugar would more profitable in the conditions described.

5.2. The case of cellulose and hemicellulose

The same approach was also applied to the conversion of the cellulose and hemicellulose contained in the bagasse by either burning the polymers or transforming them into ethanol. Although the analysis is more tedious in this case, the principle is exactly the same as above, and the same simplistic revenue-based approach suggested above for the case of sweet juice can be envisaged. Indeed, 1 ton of cellulose and hemicellulose slurry (8 200 MJ or 2 280 kWh_{th}) would yield about 210 litres of fuel–ethanol (i.e. 90.60 US$ at 0.43 US$/l) or around 450 kWh_e of electricity (i.e. 16.20 US$ at 0.036 US$/$kWh_e$). Thus, ethanol would be a more attractive product from a revenue perspective. However, this approach does not take into account the cost of processing the solids in each option. With the opportunity cost approach, depending on the proportions of steam and electricity, the shadow price of cellulose and hemicellulose varies between 5 and 7 US$/t as a fuel for heat and power generation, whereas it reaches 40.80 US$/t as feedstock for fuel–ethanol production. Thus, it would be more profitable to make ethanol from cellulose and hemicellulose than electricity. Again, no analogy can be drawn with the results obtained using the NPV approach as the systems considered differ from one approach to the other.

6. Conclusions and recommendations

An important asset of sweet sorghum is its multipurpose use, and the results from this study suggest that the best way to take advantage of this flexibility is through a flexible conversion facility capable of serving both sugar and ethanol markets, depending on the relative market prices of these two products. In short and medium term, the price of ethanol is not expected to vary much in China as fuel–ethanol is introduced to solve the provisory corn surpluses. In the longer term, however, if the market share of fuel–ethanol becomes high, its price will vary with that of gasoline and is likely to increase, while the price of sugar in China will be more and more linked to the international market price of sugar which is quite variable but also significantly less (about 200 US$/t) than that prevailing in China at present. Overall, this suggests that a sustainable strategy of bioethanol production in China cannot be based only on sweet sorghum juice due to possible competition between sugar and ethanol markets. Thus, instead of choosing between sugar and ethanol production, we recommend a biorefinery plant with a flexible operation capability (Avram and Stark, 2004; Procknor, 2003). As capital may not always be fully utilized in this type of facility, its viability will depend on the volatility of sugar and ethanol prices.

It is important to note that, at reasonable yields, making ethanol from sorghum bagasse should bring in more revenue per quantity of feedstock processed than making electricity now. From a strategic point of view, indeed, producing fuel–ethanol from cellulose and hemicellulose is more valuable than generating electricity because there are cheaper ways to generate electricity from renewable and non-food fuels. From a sustainability point of view, ethanol has a higher strategic value as a motor fuel due to the scarcity of high quality renewable liquid vehicle fuels while many options can be used to produce electricity in a sustainable way. Thus, an important opportunity is to enhance the yields and reduce the costs for ethanol production relative to the values assumed here to realize the important advantages of making a liquid fuel from this solid residue, and more thorough consideration of available technologies could reinforce this outcome. Balancing the use of bagasse between making ethanol and power also presents some important engineering optimization opportunities in terms of capital utilization that could strengthen these conclusions. In addition, the nature of the business arrangements for producing and marketing sugar, ethanol, and power must be carefully integrated into this study. Hence, more detailed analyses would be needed, based on sitespecific and technology features before finalizing the choice of a conversion option.

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