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The Importance of Utility Systems in Today's Biorefineries and a Vision for Tomorrow

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Abstract

Heat and power systems commonly found in today's corn processing facilities, sugar mills, and pulp and paper mills will be reviewed. We will also examine concepts for biorefineries of the future. We will show that energy ratio, defined as the ratio of renewable energy produced divided by the fossil energy input, can vary widely from near unity to values greater than 12. Renewable-based utility systems combined with low-fossil input agricultural systems lead to high-energy ratios.

Index Entries: Ethanol; indirect ethanol process; green power.

Introduction

Fossil resources are the major source of energy and chemicals in our society today. Among all renewable energy options, biomass is unique in its ability to potentially supply liquid transportation fuels and feed stocks for chemicals production. We believe this sector of our economy will eventually be transformed from today's fossil resource dominated system into a more sustainable biomass-based system.

The economics of production, energy security, sustainability, and rural economic development are four important policy issues for evaluating the performance of biorefineries. In this article, we discuss how utility systems affect the policy level performance for today's and tomorrow's biorefineries. Energy ratio, defined as the ratio of the renewable energy produced divided by the amount of primary fossil fuel consumed, is a useful proxy for comparing performance with respect to energy security and sustainability. We show that the energy ratio is strongly influenced by the utility system configuration and the fossil input required for growth and transport of biorefinery feed stocks. We also briefly discuss today's electrical power industry in the United States to provide background on green power markets. Our findings are used to guide performance requirements for the biorefineries of tomorrow.

An example showing the influence of utility system design on the performance of an advanced biorefinery concept for the production of

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ethanol via an indirect fermentation route is discussed. This advanced biorefinery concept has the potential to give very high-energy ratios when combined with fossil fuel efficient agricultural systems. A further advantage is that implementation is not limited to tropical or subtropical climates; temperate climates such as those found in much of the United States could support facilities based on this advanced biorefinery concept.

Today's Biorefineries

Corn processing, sugar mills, and pulp and paper mills are examples of well-established biorefineries. The United States is a dominant player in both the corn processing and the pulp and paper industries; Brazil is a dominant player in sugar cane processing. Each of these industries will be discussed using supporting data from either the United States or Brazilian industry.

Corn Processing

Corn is processed through three types of mills. The two most common are dry mills designed to produce fuel ethanol and distiller's dried grains and solubles (DDGS), and wet mill complexes designed to produce a slate of starch derivatives and animal feed products. A third type of mill, also known as a dry mill, produces corn grits, corn meals, and corn flours. The volume of corn processed through this third type of mill is small in comparison to the other two types of mills, so our discussion will focus on the first two types.

Total capacity for the United States dry mill industry today is 2590 MMgal/yr *(1)*. Individual plant capacities range from 30 to 100 MMgal (denatured)/yr of ethanol production. Capital cost for a modern grassroots facility is $1–1.50/annual gallon (denatured) of capacity *(2)*. The steam and power systems are usually very simple and are responsible for only a small portion of the capital investment.

Figure 1 is a simplified block flow diagram of a typical corn dry mill. Corn is received, cleaned, and hammer milled. The milled corn is mixed with water and enzymes then cooked. Cooking has the dual function of pasteurizing the feed and liquefying/saccharifying the starch. The whole grain mash is fed to fermentation where the dextrose liberated from the starch during liquefaction/saccharification is converted into ethanol via yeast-based fermentation. The ethanol/water mixture is distilled to a near azeotropic mixture and molecular sieve technology is used to further dehydrate the ethanol to anhydrous ethanol specification. The whole stillage from distillation is centrifuged to separate the solids (i.e., distillers wet grains) from the liquid (i.e., thin stillage). The thin stillage is evaporated, the residual solubles mixed with the wet grains, and the mixture is dried to produce DDGS—an animal feed coproduct.

The power requirement for a conventional dry mill is about 1.09 kWh/gal *(3)* all of which is usually purchased from the grid. A typical 45

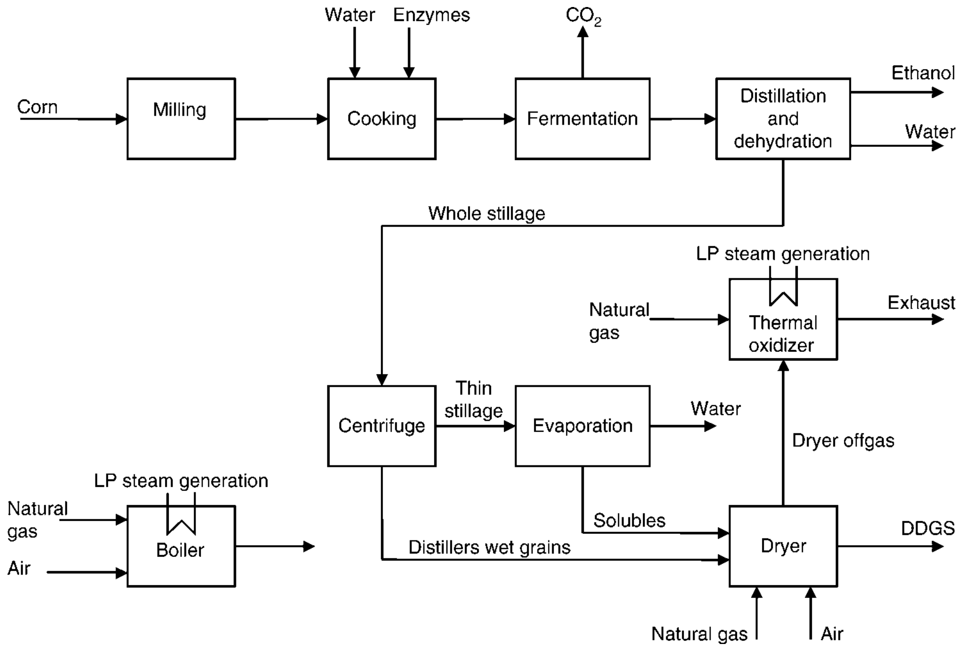

Fig. 1. Block flow diagram for a corn dry mill.

MMgal/yr ethanol plant will require 5–6 MW of base load electrical power; electrical power purchases will be roughly \$1.9–2.4 MM/yr and contribute \$0.04–0.05/gallon to the plant operating costs.

Thermal requirements for a dry mill are about 36,000 Btu/gal *(3)*. Roughly two-thirds is needed as steam for cooking, distillation, and thin stillage evaporation; the other third is typically supplied as direct fired heat for DDGS drying *(2)*. Historically, low pressure natural gas fired boilers were used to raise the necessary process steam. More recently, steam generation has been tied into the thermal oxidizer of the DDGS dryer emission control system. Natural gas is combusted to provide heat for DDGS drying, the dryer offgas is sent to a thermal oxidizer fired with supplemental natural gas as needed, and the hot gases from the thermal oxidizer are used to raise process steam. With natural gas valued at \$6/MMBtu, a typical 45 MMgal/yr ethanol plant will purchase about \$11 MM/yr of natural gas, contributing about \$0.25/gallon to the plant operating cost. Natural gas purchases are the second largest operating cost in a typical dry mill, second only to corn. Financial instruments are often used to manage operating risk with respect to both corn and natural gas prices.

Figure 2 is a simplified block flow diagram for a corn wet mill facility. Wet mill facilities are technically more complex than corn dry mills. The front-end wet mill physically fractionates corn into its constitutive parts (i.e., starch, fiber, protein, and germ/oil). The fiber and protein fractions are sold as animal feeds; oil is extracted from the germ and is refined for human consumption. The starch slurry produced in the mill house is

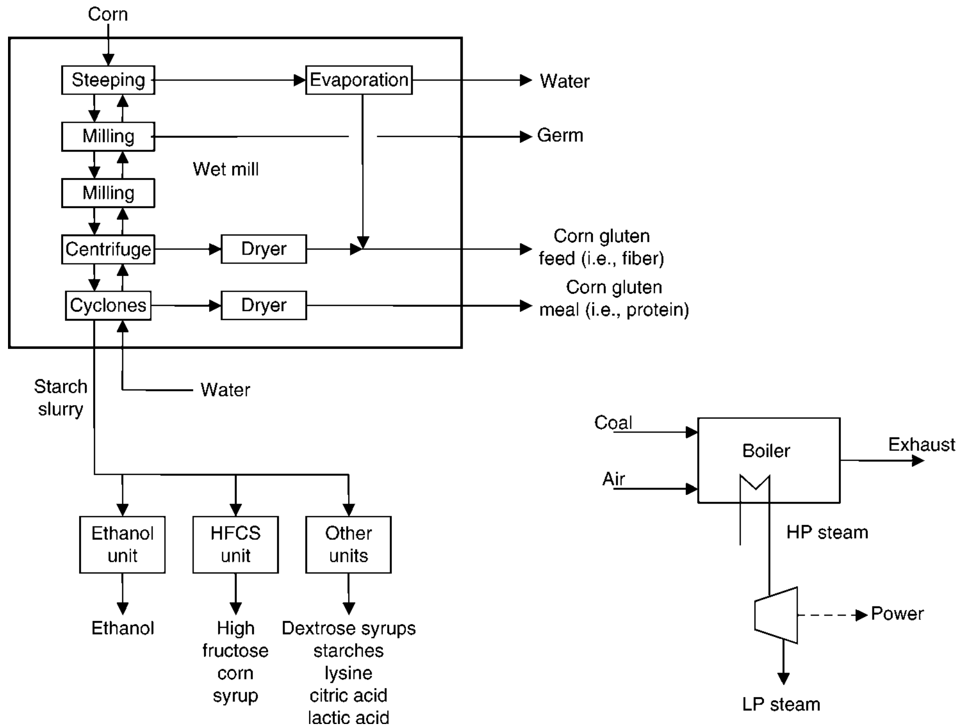

Fig. 2. Block flow diagram for a corn wet milling complex.

further processed by downstream units into a myriad of products including ethanol and high-fructose corn syrup. Current total wet mill capacity for ethanol production in the United States is 1109 MMgal/yr *(1)*, or slightly more than one-quarter of the industry's total grind capacity *(4)*.

Wet mill facilities are typically larger than dry mills. Grind capacities for an individual mill range from 50,000 to 500,000 bu/d of corn, with a typical mid-sized wet mill grinding about 200,000 bu/d or roughly 4300 mt (dry)/d. As a comparison, a 45 MM gal/yr (denatured) dry mill grinds about 47,000 bu/d or roughly 1000 mt (dry)/d. Capital costs for a wet mill are difficult to estimate because of all the possible configurations, but "rule-of-thumb" values are around \$2.50–3/gall of capacity if all the starch were converted to ethanol.

Steam and power systems are also typically more complex. Large wet-mills often use coal fired boilers to produce high-pressure steam which is then let down across a steam turbine to produce power and low-pressure steam for process heating. Natural gas fired combined heat and power systems are found more frequently in small to mid-sized facilities. Electrical power and thermal requirements for a wet mill complex producing ethanol are approximately the same as for a dry mill when compared on a per bushel grind basis. Thus, the power to heat ratio for both types of facilities is roughly 0.10–0.15 depending on whether superheated steam or fired heat is used for the drying operations. This relatively low ratio suggests that most cogeneration systems were designed primarily for steam production. Galitsky et al. *(5)* estimates that in 1998 the United States wet mill industry, as a whole, produced only 21% of its electrical needs internally and purchased the balance of power from the grid. As in a dry mill, fuel costs are typically the second largest operating cost in a wet mill, second only to corn.

There has been much discussion in the literature over how to evaluate the energy producing capabilities of renewable energy systems. A life cycle assessment is a comprehensive accounting of all the inputs and outputs required to produce a good or service, and should conform to the standards set forth by the International Standards Organization *(6)*. Although life cycle assessments are a rigorous means of evaluating renewable energy systems, conducting such an analysis is time consuming. In this article we use the short cut analysis method known as "net energy value." A net energy value analysis estimates the amount of fossil fuel required to produce a biobased fuel such as ethanol. The energy ratio is defined as the ratio of the renewable energy produced divided by the amount of fossil fuel used in production. Values greater than one imply success at harvesting sunlight and converting it into fuel. A net energy value analysis is less comprehensive than a life cycle assessment. For example, a net energy value analysis ignores the impact of ethanol on the performance of light duty vehicles whereas the boundaries for a life cycle assessment would likely be drawn to include this in a "farm-to-wheels" assessment. Although less comprehensive than a true life cycle assessment, the net energy value shortcut method has the benefit of being easy to calculate and the results can be used to qualitatively compare the energy producing capabilities of various ethanol production systems.

Workers at the United States Department of Agriculture (USDA) have authored a series of net energy value analyses for fuel ethanol production using domestic corn as the primary feedstock *(3,7–8)*. Table 1 reproduces the USDA net energy analysis for the data reported in ref. 3. They give an industry composite energy ratio of 1.34, meaning that a gallon of ethanol produced by the industry only contains 34% more energy than the fossil fuels used in its production. Although the energy ratio is greater than one, it is does not exceed one by a large amount. As most of the fossil fuels are consumed during conversion of grain to ethanol, today's ethanol industry can be viewed as a means to convert coal and natural gas (and to a lesser extent petroleum) into a liquid transportation fuel.

Historically, ethanol has sold in the United States at a premium to unleaded gasoline even after adjusting for the effect of the excise tax exemption. The ethanol industry's capacity was relatively small and ethanol tended to compete in the fuel pool as either an oxygenate or octane blending component. The market situation has changed significantly over the past few years. Crude oil prices have risen from $20–25/barrel to over $50/barrel, but ethanol prices have remained relatively stable. Today

Table 1
Energy Ratios for Ethanol Plants

	Values are in Btu/gal EtOH (neat)[a]							
	Standard dry mill	Standard wet mill	Dry mill w/landfill gas	Dry mill w/gasifier	Cane mill + distillery, average	Cane mill + distillery, best practices	Transitional indirect w/ combined cycle	Advanced indirect
Feed stocks								
Process	Corn kernels	Corn kernels	Corn kernels	Corn kernels	Cane juice	Cane Juice	Corn kernels	Lignocellulose
Utilities	Natural gas and coal	Natural gas and coal	Landfill gas and coal	Wood wastes	Bagasse	Bagasse	Stover, natural gas and coal[d]	Lignocellulose
Fossil energy use								
Crop production	21,803	21,430	21,803	21,803	6627	6076	15,566	2339
Crop transport	2284	2246	2284	2284	1792	1427	1631	2886
Other feed stocks	0	0	1369	2085	0	0	16,573	0
Ethanol conversion	48,772	54,239	11,482	0	2061	1556	20,833	0
Ethanol distribution	1588	1588	1588	1588	0	0	1588	1588
Subtotal	74,447	79,503	38,526	27,760	10,480	9059	56,191	6813
Coproduct credits								
Mill coproducts	13,115	14,804	13,115	13,115	0	0	10,670	0
Fuel or power export	0	0	0	0	7038	12,368	57,425	0
Subtotal	13,115	14,804	13,115	13,115	7038	12,368	68,095	0
Net energy value[b]	22,629	19,262	58,550	69,316	76,734	83,486	95,865	77,148
Energy ratio[c]	1.37	1.30	3.30	5.73	8.32	10.22	3.11	12.32

[a]Multiply by 0.2787163 to obtain MJ/m^3. The cane mill entries are on a lower heating value basis and the calculations use Macedo's value for the lower heating value of ethanol (80,176 Btu/gal). The other entries are on a higher heating value basis and use the USDA's value for the higher heating value of ethanol (83, 961 Btu/gal).

[b]Net energy value heating = value of ethanol – (fossil energy use – coproduct credits).

[c]Energy ratio = (Heating value of ethanol + fuel or power export)/(fossil energy – mill coproducts).

[d]This case considers adding an indirect ethanol process to an exisitng wet mill. Corn stover is used as the main fuel for the indirect unit's utilities; natural gas and coal are the main fuels for the wet mill's utilities.

ethanol sells at roughly two-thirds the price of unleaded gasoline after adjusting for the effects of the $0.51/gallon excise tax exemption. This suggests that ethanol's role in the fuel pool has changed from an oxygenate or octane blending component to an energy source *(9)*.

US ethanol production is still relatively small when compared with demand for liquid transportation fuels. In 2003, the United States transportation sector consumed 26.8 Quads in the form of gasoline, diesel, and other fuels *(10)*. In that same year, ethanol supplied 0.239 Quads, or about 1% of our country's consumption of transportation fuels. Thus, despite recent growth of the industry, ethanol does not currently make significant contributions to our country's energy security.

US natural gas prices tend to track crude oil prices. The recent run-up in crude oil prices have been accompanied by a rise in natural gas prices from historic levels of $2–3/MMBtu to today's levels of $6–7/MMBtu. The high price of natural gas makes it difficult for corn processors to justify addition of natural gas fired cogeneration facilities. Some recently proposed dry mills have included coal fired boilers *(11)*. Although coal is a much less expensive energy source, coal fired utilities increase dry mill capital costs by 40–60% and have poor environmental performance when compared with natural gas fired utilities. There are two other niche modifications to utility systems being pursued today:

1. Some processors are substituting landfill gas for a portion of their natural gas needs. Successful projects require that landfill gas is locally available and can be purchased at a discount to natural gas on an energy content basis. Landfill gas substitution leads to improvements in the net energy value performance for the facility. Table 1 presents a net energy value analysis for a conventional dry mill that purchases electrical power from the grid and uses landfill gas to replace 100% of its natural gas requirement. Landfill gas is considered a renewable energy source, so the energy content of the gas itself is not included in the analysis; the other feed stocks category is an estimate of the fossil energy required for compression and processing at the landfill site. The energy ratio jumps to 3.3 when the entire natural gas requirement is replaced by landfill gas, a considerable improvement over a conventional dry mill.
2. Central Minnesota Ethanol Cooperative is pursuing a waste wood gasification project *(12)*. The syngas will be used to fire the thermal oxidizer/boiler at their existing corn dry mill. The heat released will be used to raise high-pressure steam, which in turn will be used to produce power and low-pressure steam for process needs. Capital cost is projected to be $15 MM; the existing plant capacity is about 20 MM gal/yr, so when implemented this will be a significant capital project. The benefit will be a complete elimination of natural gas and electricity purchases. Table 1 presents an order-of-magnitude net energy value analysis under the assumption that the fossil energy

consumed to produce and transport wood waste is 2085 Btu/gal. The energy ratio increases dramatically to 5.73.

Both examples show that changes to the utility system can improve plant economics while improving sustainability and maintaining rural economies. It is important to note that "green-ness," as indicated by an energy ratio much larger than one, does not necessarily imply a lignocellulosic-based fermentation. Starch fermentations can provide reasonably high-energy ratios when the utilities for the plant are provided by renewable resources. The long-term driver for lignocellulosic fermentation R&D is that lignocellulosics, unlike corn starch, are projected to be capable of providing enough feed stock to make a significant contribution to our country's energy supply *(13)*.

Sugar Mills

Sugar is produced from either sugar beets or sugar cane. Sugar beets are grown in temperate climates of North America and Europe. Tropical and subtropical climates support sugar cane production. The beet sugar industry supplies roughly 30% of global sugar demand; the cane sugar industry provides the balance of demand *(14)*.

The slicing season for sugar beets is about 100 d in Europe and can extend to as long as 250 d in North America. Beet processors operate integrated milling and refining operations. Thick juice storage/processing and molasses processing strategies are sometimes used to extend the operating season. Exhausted beet pulp is usually processed and sold into animal feed markets, thus it is not available as fuel for the factory. The utilities for beet factories are usually derived from fossil resources. Combined heat and power systems using a boiler/steam turbine cycle are common. Power and steam requirements for an energy efficient mill are 3.1 kWh/100 kg beet and 17–22 kg/100 kg beet *(14)*. This gives a power to steam ratio of 0.23–0.30, at the high end of what can be provided by a simple boiler/turbine cycle.

The crushing season for sugar cane spans 5–8 mo. Unlike the beet sugar industry, most cane mills are not integrated with a refinery. Sugar refineries operate year-round to produce white sugars from the raw sugar produced by the mills. Colocating a mill with a refinery has the advantage of improving capital utilization as utilities and other infrastructure can be shared.

Brazil is by far the largest producer of raw sugar in the world. Its industry is unique in that significant capacity has been installed for both raw sugar and ethanol production, allowing integrated factories to swing production between the two products based on market conditions. In 1997, the total amount of gasoline, ethanol and diesel consumed in Brazil for transportation was 81.2×10^9 L, 16% of which was derived from domestically produced ethanol. Reference *(15)* gives further details of the policy level performance of the Brazilian industry.

Figure 3 is a simplified block flow diagram for a typical Brazilian cane mill. The harvested cane is received, cleaned, chopped if harvested as whole

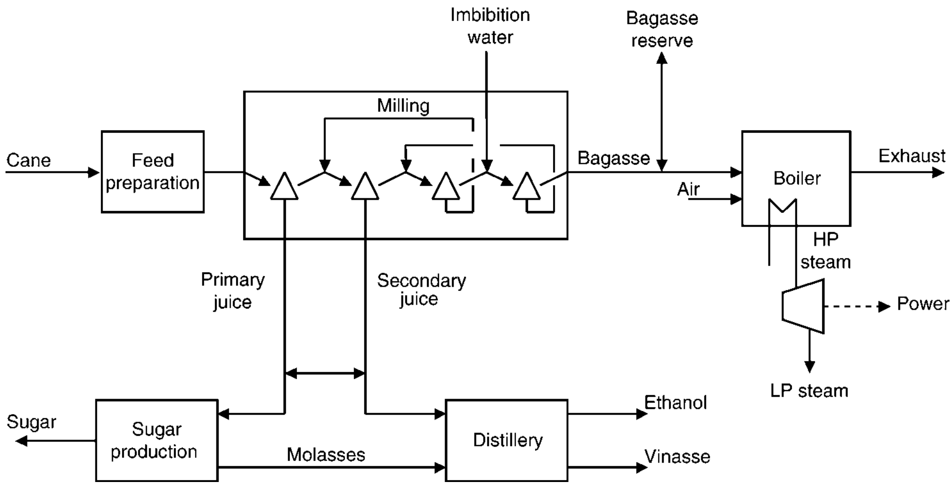

Fig. 3. Block flow diagram for a Brazilian cane mill.

cane, shredded then passed through the first of four to six milling tandems. The juice from the first mill, called the primary juice, is used mostly for sugar production. The bagasse (i.e., the fibrous remains of the cane plant after extraction of the sugar juices) from the first mill is further extracted in a series of three to five mills to produce a secondary juice and a final mill bagasse that is nearly exhausted of soluble sugars. Imbibition water is added at the back end of the milling train and the expressed juice from each mill is fed to the previous mill to provide countercurrent extraction. The secondary juice has lower concentration of sucrose and higher levels of nonsugar impurities when compared to the primary juice. The secondary juice is split between sugar production and ethanol production based on management's targets for sugar and ethanol. The distillery includes the fermentation, distillation, and dehydration steps used to produce commercial fuel alcohol. The carbohydrate feed to the distillery is a mixture of secondary juice and molasses from sugar production (i.e., the residual solubles after crystalline sugar has been recovered). In addition to ethanol, the distillery also produces vinasse, which contains the solubles not converted to ethanol during fermentation. Vinasse is recycled back to the cane fields as a fertilizer.

The bagasse from the last milling tandem is combusted in the plant boilers and the heat released is used to produce process steam, mechanical power to drive the milling equipment, and electricity to drive the rest of the rotating equipment in the factory. The three main factors affecting the mill energy balance are:

1. the fiber content of the incoming cane,
2. the energy efficiency of the juice evaporation and syrup crystallization steps, and
3. the energy efficiencies of the bagasse boiler and associated steam and power generation systems.

Most mills manage their operations so that bagasse provides all of the fuel to the mill's boilers during the crushing season, and the mill is usually operated so there is no net import or export of steam and power. Usually a slight excess of bagasse is held in reserve to cover fuel needs during start-up or shut down of the factory. Any bagasse produced in excess of the reserve needs is sold as fuel to other industrial facilities (e.g., orange juice processors), sold as a coproduct (e.g., source of pulp for papermaking, and various agricultural applications) or otherwise disposed. Coal, fuel oil, or another fossil fuel source is used to fuel the boilers only when the bagasse supply has been eliminated. Combined heat and power systems based on boilers/steam turbines are also common throughout the industry.

A current trend in Brazilian mill modernization is to improve electricity production. Historically, electricity prices in Brazil were very low because there was an oversupply of generating capacity. Hydroelectric plants supply 82–87% of the grid electricity *(16)*. With poor market conditions for electricity, it was difficult for mills to justify investments to increase electricity production. In fact, up until 1985 most Brazilian mills were not self-sufficient with respect to electricity. Low thermal efficiencies in both the boiler and process operations were acceptable, perhaps even desired, as this was a way to dispose of bagasse. The oversupply in hydroelectric generating capacity has slowly been worked off over the past two decades. Today, market conditions are favorable for export electricity sales. Cane sugar mills currently provide about 6.1% of the grid power consumed in the service area for Paulista Company of Light and Power, a power utility in São Paulo state *(16)*.

The experience of the Brazilian industry with respect to export electricity has been repeated throughout the cane sugar industry. Mills have installed energy efficiency projects that reduce their steam usage, resulting in extended bagasse supplies and/or higher power export revenues. Boiler house improvements focus on increasing the pressure of steam generation and improved steam turbine efficiencies. High-efficiency swirl-burner combustion systems have been installed in Australia and Cuba, leading to boiler combustion efficiencies of 81–89.6% vs 58.8–67.1% for older designs *(17)*. The literature also contains much discussion about whether cane trash collection from the fields (i.e., leaves and tops) and gasification projects are worthwhile prospects for increasing export electricity production.

Macedo has published a series of net energy value analyses for the Brazilian ethanol industry *(18–20)*. Table 1 presents the industry average case from Macedo's analysis of the 2001/2002 season *(18)*. His reference plant is a seasonally operated mill + distillery that only produces ethanol (i.e., Macedo has simplified the analysis by excluding sugar and export electricity production). Power consumption is reported at 28.9 kWh/t cane (electrical: 12.9 kWh/t, mechanical: 16 kWh/t) and steam consumption ranges from 220 to 330 kWh/t cane, giving a process power:steam ratio requirement of 0.09–0.13. However, these utilities need not be counted in the net energy analysis as they are supplied by combustion of bagasse—a renewable resource. In fact, Macedo takes a credit for the bagasse in excess of that needed to operate the facility. He reports an energy ratio of 8.32 for the industry average and 10.22 for the best practices case.

Quantitative comparison with the USDA corn ethanol analysis is perilous because the underlying assumptions differ among the two analyses. For example, there are differences as whether higher or lower heating values are used for the basis, differences on whether to include energy embodied in buildings and equipment, and differences on whether to include energy for ethanol distribution. However, after adjustments to reconcile the analyses, the Brazilian ethanol industry appears to enjoy a significantly higher energy ratio than the United States industry. The use of green utilities in the ethanol conversion step is the chief reason for the difference. Reduced fossil fuel input to the agricultural system (e.g., lower fertilizer application rates) and bagasse fuel/green power export are also contributing factors.

Pulp and Paper Mill

A modern pulp and paper mill is a highly evolved and integrated system. The industry is by far the largest practitioner of lignocellulosic pretreatment processes to extract valuable components from biomass. We restrict our coverage to Kraft pulp mills because this is the predominant pulping technology used in North America.

A typical Kraft mill supplies all of its steam requirements and a substantial portion of its electrical needs internally. As shown in Fig. 4, a common configuration uses a combined heat and power system with two boilers raising high-pressure steam and a noncondensing steam turbine to produce power and low-pressure steam for process needs. A majority of the high-pressure steam is generated by the Tomlinson black liquor recovery boiler. This boiler has the dual function of regenerating process chemicals and producing high-pressure steam. It is fueled by the soluble lignin and hemicellulose components of black liquor, originally extracted from the wood chips during digestion. The hog fuel boiler provides the balance of steam and is fueled by bark and other waste wood. Roughly 65% of the mill's electricity requirement is produced internally; the balance is purchased from the grid. A mill also uses some fuel oil or natural gas to operate the lime kiln, part of the chemical cycle in the Kraft process.

We will not present a net energy analysis for the pulp and paper industry because few facilities currently produce ethanol. However, one would expect fairly high energy ratios would result as renewable fuels would be used to generate most of the steam and power utilities. Furthermore, the fossil inputs required for forestry operations are a fraction of those required for corn production *(21)*.

Although Kraft pulping technology is very mature, some new technology is being considered to enhance the energy integration, yield

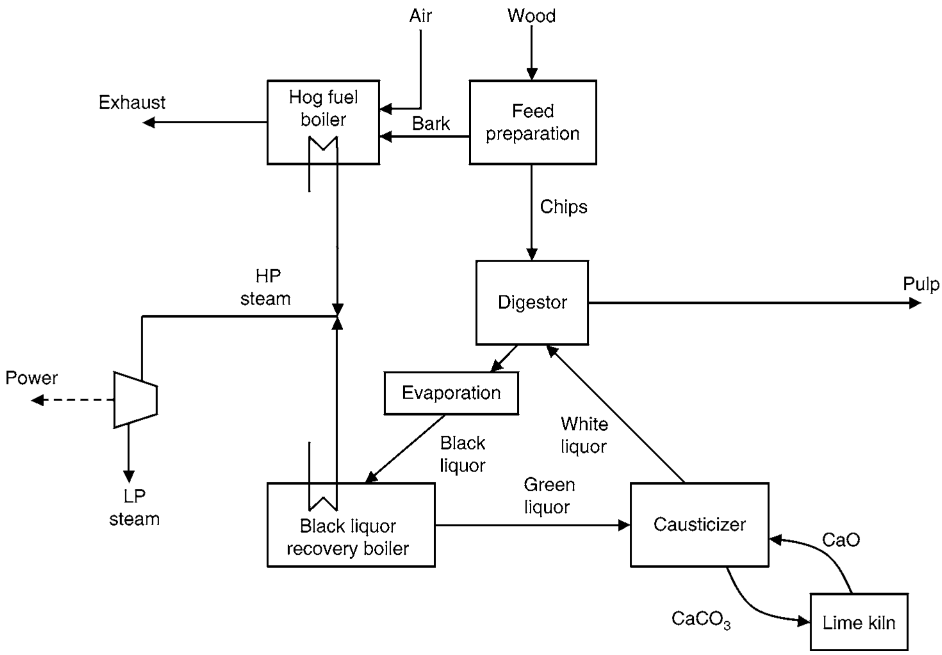

Fig. 4. Block flow diagram for a kraft pulp mill.

and flexibility of the process. Black liquor gasification is currently being tested at several demonstration scale industrial facilities. When implemented at full scale, black liquor gasification will replaced the functionality currently provided by the Tomlinson black liquor recovery boiler. Implementation of this technology will also enable polysulfide pulping, leading to 4–6% higher pulp yield for the mill.

The syngas produced by gasification can be used to replace the fossil fuel currently used to fire the lime kilns and also as a fuel for cogeneration of electricity and steam. The reference plant in *(22)*, representative of a modern integrated Kraft pulp and paper mill located in the Southeastern United States, shows the current Tomlinson-type configuration requires a process power to steam ratio of 0.47. This high ratio cannot be met by a simple boiler plus noncondensing steam turbine cycle. Black liquor gasification produces a gaseous fuel that can be used to fuel a gas turbine-based combined cycle unit. Combined cycle cogeneration units are capable of meeting high ratios of power to steam. Energy balance calculations show that a full-scale replacement of the Tomlinson boiler with black liquor gasification plus combined cycle cogeneration will augment power generation to the point that the mill will become a net exporter of power while still maintaining its steam balance *(22)*. In fact, the economic analysis in *(22)* suggests that mills may wish to purchase and gasify additional wood residuals to further boost export electricity production beyond that attainable with normal processing of pulp logs.

Today's US Electrical Power Industry

The US electric power industry was highly regulated for many decades. Industry goals were very simple: reliable low-cost supply of power. The result was the construction and operation of massive coal fired and nuclear power plants. These plants had high capital costs but very low operating costs. The high capital costs were not viewed as risky as the industry was regulated and capital charges could be amortized into the rate base at a low discount rate over a very long time period.

Ever increasing environmental standards and industry deregulation brought many changes to the US power industry in the 1990s. Lower capital cost projects, based both on combined heat and power installations at existing industrial facilities or as stand-alone gas fired combined cycle plants, dramatically improved the efficiency of power generation and brought the promise of low cost generation. The new players in the industry were much more responsive to market forces. Along with deregulation came new market forces such as green power programs. Green power, originally introduced as a competitive marketing tool in deregulated environments, was viewed as one way that new producers could compete against older utilities.

Today, green power programs are available at over 350 utility companies operating in 33 states *(23)*. Approximately 1% of US electricity sales are through green power programs. Typical green power premiums are approx \$0.025–0.03/kWh. Green generation capacity is mostly from wind, landfill gas, solar, or small scale hydroelectric power. Co-firing of biomass in existing coal plants and stand-alone biomass fired is also practiced *(24)*.

The details of green power program implementation vary depending on each state's regulatory environment. Certain states have passed legislation requiring utilities to produce a certain percentage of their power from renewable resources. In fully deregulated markets, the customer may be required to switch from their default power provider to a provider that offers a green power package. In regulated markets, the utility offers green pricing programs to offset the higher production costs for green electricity. A third alternative, usually pursued by industrial rather than residential consumers, is to participate in green power trading programs through the purchase of renewable energy certificates (REC). REC also known as green tags, are also used by the utilities to support their green power programs.

An important benefit of green power generation is that it reduces the amount of NO_X and SO_X emissions produced per megawatt of generation in a utility's portfolio. NO_X and SO_X credits are separable from the green tags; they can be sold into the existing NO_X and SO_X trading systems. Old line utilities are becoming more interested in green power generation because these trading systems can be used to delay the large capital expenditures needed to modernize existing coal fired power plants.

Recent statistics on US power generation by fuel source are: coal–51%; nuclear–20%; natural gas–16%; hydroelectric–7%; others–6% *(10)*. Most coal and nuclear generating capacity is for base load power; today's high price of natural gas relegates its use to intermediate and peaking plants. It is very difficult to compete head-to-head with base load power plants without some type incentive such as green power credits. As was found in Brazil, we believe that in the long-term, biomass-based US biorefineries will eventually compete in electricity markets. Companies will decide that it makes more sense to invest in biorefinery cogeneration projects rather than massive new base load facilities to satisfy the incremental base load power demand caused by natural expansion of the economy.

In the short-term though, it is uncertain whether biorefineries will compete in electricity markets. Although petroleum and natural gas may become scarce, US coal reserves are quite large, so base load electricity prices should stay low in the foreseeable future. Green power programs may not be available at every biorefinery site. Production of export power drives-up capital projections for future biorefineries, further exacerbating risk for first-of-a-kind installations. This suggests that the technology developed for future biorefineries should provide flexibility with respect to business decisions on whether electrical power is to be exported from the facility.

Tomorrow's Biorefineries

Most experts agree that lignocellulosic feed stocks will eventually be required if renewable fuels are to make a significant contribution to our country's energy security. For example, the US DOE/USDA recently issued a joint report evaluating the land resources required to displace about 30% of our petroleum consumption. Their projections are that starch-based grains will contribute only 6% of the required feed stock; lignocellulosics will provide the balance *(13)*. Modern breeding tools can be used to create lignocellulosic crops with desirable agronomic and bioprocessing properties. It is not difficult to imagine a future in which dedicated farms grow energy crops designed specifically for biorefinery operations.

The technology used in biorefining operations will also likely evolve. One view of the future for ethanol production suggests that current direct fermentation technology will be merely augmented with front-end processes for lignocellulosic pretreatment and hydrolysis. The resulting hydrolyzate will then be converted into ethanol using direct fermentation technology, using a route similar to todays' with certain adaptations to account for differences between biomass and corn starch hydrolyzates. Although technically viable, this viewpoint fails to appreciate the poor match between the capabilities of direct fermentation technology and the distribution of energy among the fractions of the lignocellulosic feed stock.

Consider processing a typical lignocellulosic biomass into ethanol via direct fermentation of the biomass hydrolyzate. Roughly one-third of the energy content of the feed is present in the form of cellulose. Cellulose can be converted into dextrose with appropriate pretreatment and hydrolysis of the feedstock and then fermented with traditional direct fermentation yeasts or similar micro-organisms. Lignin and other nonfermentable materials account for about 40% of the energy content of the feed. The balance of the feed energy is in the form of hemicellulose, which produces a mixture of five and six carbon sugars upon pretreatment and hydrolysis of the biomass feedstock. Genetically engineered micro-organisms that produce ethanol from both five and six carbon sugars must be utilized to obtain high yield from the hemicellulose derived sugars as no wild-type micro-organisms exist that are capable of converting mixed sugars. Thus 40–60% of the chemical energy of the starting material (i.e., all of the lignin and nonfermentables fraction plus any unfermented materials from the cellulose and hemicellulose fractions of the biomass) is not available for ethanol production via direct fermentation.

So what can be done with the nonfermentable matter? One option could be to produce lignin-derived chemicals, such as adhesives, but these markets will become quickly oversaturated. Another option is to burn the nonfermentables, but very low process efficiencies result unless the heat released is used to generate steam and/or electricity. The amount of heat available is beyond the needs of the process, so the facility is forced to either compete for sales in electricity markets or accept low overall process efficiency.

Another view suggests radically different technologies will be used in the biorefineries of tomorrow. Concepts for advanced biorefineries often include biomass gasification/syngas production, bioprocessing, or combinations of the two. These technologies provide a better match between the energy distribution of the feed and the process technology capabilities. A common feature of syngas fermentation *(25)*, catalytic production of ethanol or mixed alcohols from syngas *(25)*, and the indirect fermentation process *(26,27)* is that gasification technology is used to access the chemical energy stored in lignin and other nonfermentable fractions of lignocellulosic feed stocks. Some benefits of these advanced concepts include: high overall process efficiency, good economics, and a good alignment with the other policy objectives mentioned in the Introduction. A downside of these advanced concepts is their high complexity, which increases risk for first-of-a-kind developments.

ZeaChem Inc. (Lakewood, CO) is engaged in the development of the indirect fermentation route for ethanol production. Our core chemistry can be broken down into three steps, as illustrated in Fig. 5 for the case of dextrose as the fermentable carbohydrate. In the first step, a homoacetogenic fermentation is used to produce acetic acid from carbohydrates at near 100% carbon yield. The acetic acid is then esterified with an alcohol to produce an ester. The ester undergoes hydrogenolysis to produce the desired ethanol

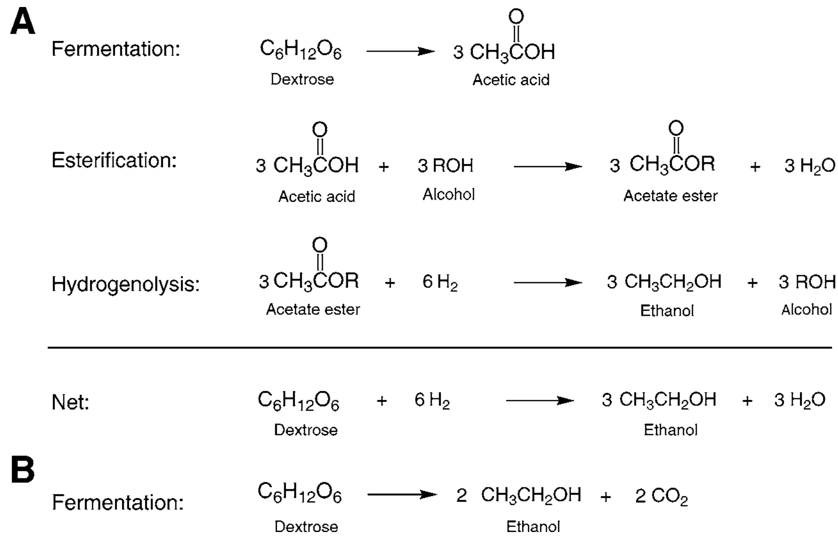

Fig. 5. Comparison of process chemistries. **(A)** Indirect ethanol route and **(B)** direct fermentation.

product and the recycle alcohol for the esterification step. The net result of the indirect route for ethanol production is a 50% improvement in molar yield compared to direct fermentation technology (i.e., three moles of ethanol per mole of six carbon sugar vs two moles ethanol per mole of six carbon sugar).

The energy for the third mole of ethanol is supplied by hydrogen. Biomass gasification is a particularly attractive means of hydrogen production as it converts the chemical energy stored in lignin and other nonfermentables into hydrogen, which in turn can be converted into the chemical energy stored in the ethanol product. This, combined with the fact that many homoacetogens metabolize both five and six carbon sugars, means that the chemical energy of all three major biomass fractions are converted into ethanol at high overall energy efficiency.

Figure 6 is a block flow diagram of one way to implement the indirect route during the current transitional period between starch and lignocellulosic feeds. Fermentable carbohydrate is supplied by a corn wet mill. Corn stover is gasified and further processed to recover hydrogen for the hydrogenolysis step. A fraction of the syngas is diverted for steam and power production. We recently completed a techno-economic study of the transitional implementation shown in Fig. 6, in which the indirect plant was assumed to be a grassroots facility located "across-the-fence" from an existing corn wet mill *(26)*. The corn wet mill provided starch hydrolyzate to the ethanol facility; the ethanol facility produced its own utilities.

Rigorous material and energy balances were calculated using HYSYS 3.2, a commercial process simulator. A factored capital cost estimated was assembled, operating costs and revenues were estimated using the material balance as the basis, and discounted cash flow calculations were done to

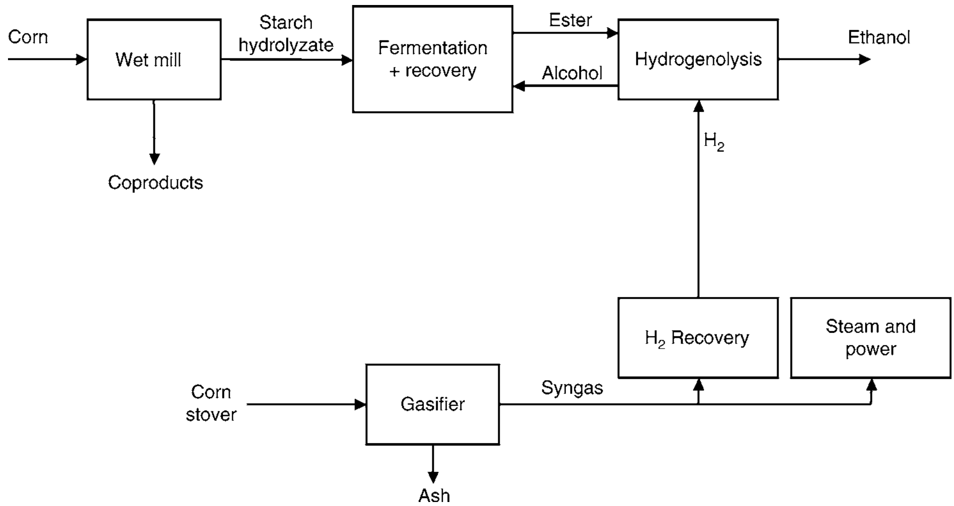

Fig. 6. Block flow diagram for a transitional indirect ethanol facility.

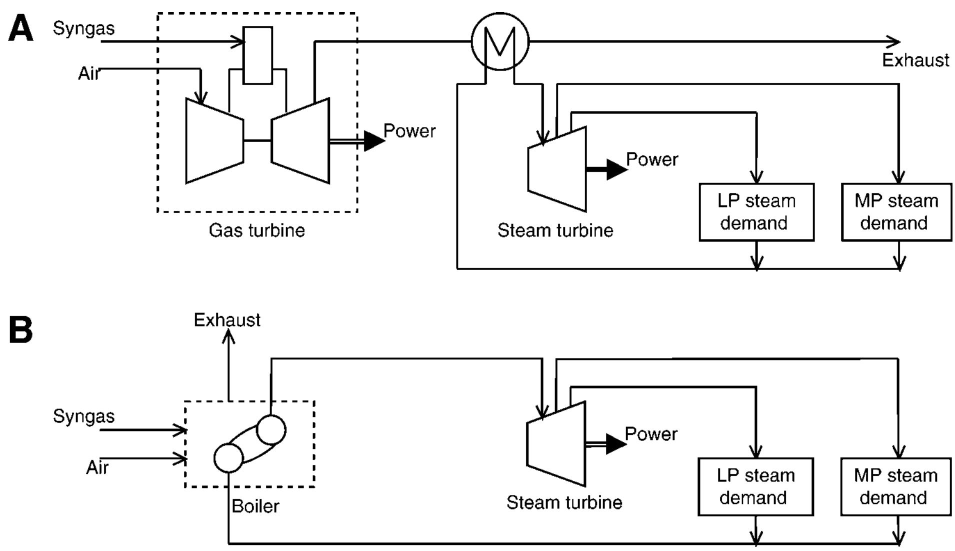

Fig. 7. Utility system configuration for the transitional indirect ethanol facility. **(A)** Combined cycle and **(B)** boiler/steam cycle.

combine the capital, operating and revenue estimates into standard performance measures. Both single parameter and Monte Carlo simulation methods were used to understand the sensitivities to various model assumptions.

One of the sensitivity studies was a comparison between two different implementations of the steam and power block. One implementation, shown in Fig. 7A, assumes a gas turbine-based combined cycle system with a noncondensing steam turbine. The combined cycle system provides the process steam requirements, all of the process electrical requirements,

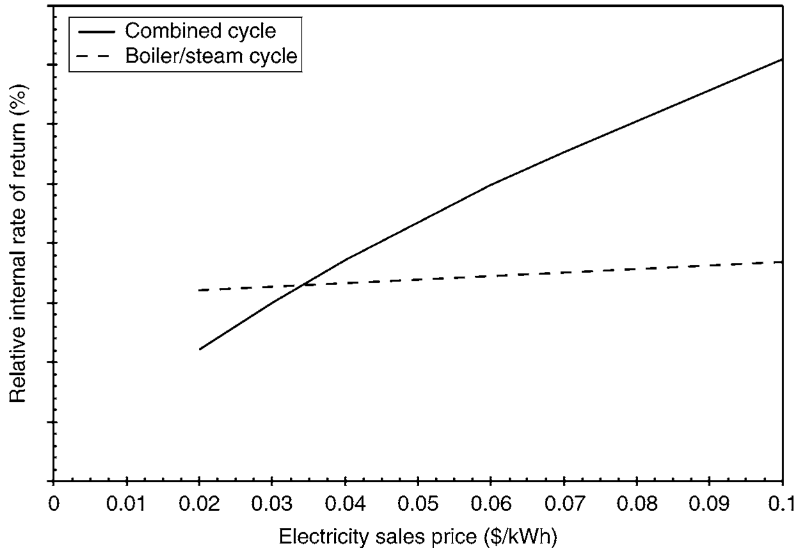

Fig. 8. Effect of utility system configuration on projected internal rates of return.

and a significant amount of export electricity for sales on the grid. The other implementation, shown in Fig. 7B, assumes the syngas is combusted in a boiler and the heat released used to produce high pressure steam, which in turn is expanded through a noncondensing steam turbine to produce electricity and process steam requirements. In this second case, the ethanol plant is nearly in power balance. The process steam requirement between the two cases is essentially identical. Because the combined cycle case produces a significant amount of export electricity, the combined cycle case has a higher stover feed rate and a larger gasification facility when compared with the simple boiler/steam cycle case.

Figure 8 shows the sensitivity of the internal rate of return for the two cases with respect to variations in the assumed selling price for export electricity. The two curves intersect at an electricity selling price of about $0.034/kWh. If the local value of base load green power is less than $0.034/kWh, the analysis suggests the boiler/steam cycle should be installed. If the local value of base load green power is greater than $0.034/kWh, the combined cycle system should be installed. A further risk analysis would probably lead to the conclusion that slightly higher electricity prices are needed to fully justify investment for the combined cycle option because it is more capital intensive. Additional creative business strategies, such as separating ownership of the utility system from ownership of the process plant, may also be needed to mitigate risk.

Table 1 presents an energy ratio analysis for the combined cycle case. The other feed stocks category reflects the fossil inputs required for stover production, harvesting and transport under the assumption that 1.69 MJ of nonrenewable energy is required per kg of harvested corn stover *(28)*. An

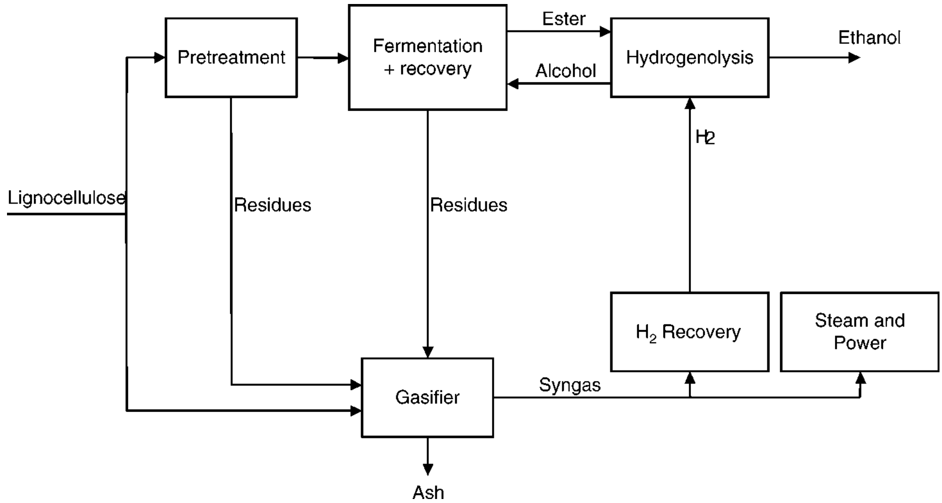

Fig. 9. Block flow diagram for an advanced indirect ethanol facility.

energy ratio of 3.11 is projected. Although the ethanol plant itself produces all of its steam and power from renewable resources, this modest value for the energy ratio is a result of the fact that fossil fuel consumption for the ethanol conversion step is still significant since the wet mill utilities are assumed to be supplied from fossil resources. The agricultural system used to produce corn kernels and stover is also a significant consumer of fossil fuels.

Many other implementations of the indirect process could be envisioned. For example, an all lignocellulosic case could be assembled by replacing the wet mill with biomass pretreatment and hydrolysis steps (*see* Fig. 9). Lignin rich fermentation residues would replace most of the stover used as feed for the gasifier. Significant improvements in the energy ratio would result if this advanced biorefinery concept were combined with improved agricultural systems for production and delivery of lignocellulosic feed stocks. The Advanced Indirect entry of Table 1 was derived from the values in *(21)* for fossil inputs required for lignocellulosic crops and an assumed chemical energy efficiency in ethanol conversion of 65% with the balance of feedstock energy used for utility production with no export/import of steam or power. An energy ratio of 12.32 is projected. Further improvements in energy ratio would result if the assumptions were changed to allow export of excess electrical power. Biorefineries with such high values for the energy ratio are not limited to tropical or subtropical climates; temperate climates throughout much of the US could support such a system.

Discussion

We have assumed the four main policy drivers affecting future biorefineries are economics, energy security, sustainability, and rural economic development. We showed that biorefinery utility systems are an important factor in policy level performance. Petroleum and natural gas fired systems look like nonstarters on all four policy level measures; coal fired systems only satisfy the first two policy objectives; biomass fired utility systems have potential to satisfy all four policy objectives.

We have outlined several desirable features for the process technology used in the biorefineries of tomorrow. Ethanol production technology should have flexibility with respect to feed stock to aid the transition from starch to lignocellulosic-based feed stocks. Ethanol production technology must be able to efficiently handle lignin and other non-fermentables; gasification based technologies appear to have a significant role in future biorefineries. Lastly, ethanol production technology needs to provide flexibility with respect to business decisions on power export.

Improved agricultural systems are also a likely feature of the biorefineries of tomorrow. Modern breeding tools can be used to create lignocellulosic crops with desirable agronomic and bioprocessing properties. Reduction in fossil fuel consumption for growing and harvesting plus ease of processing in biorefining operations will likely become important traits. Year round supply, or ability to store seasonally harvested crops, is another desirable feature. Seasonal operation of sugar mills results in low capital utilization, which makes it hard to justify capital investments to modernize existing facilities.

Finally, we suggest that the biorefineries of tomorrow will likely be capital intensive. The low capital intensity of a corn dry mill is a consequence of an easy to process feed stock and the low complexity of the supporting utility system. However, we have shown that today's conventional corn dry mill has a relatively low energy ratio and thus has poor policy level performance. We believe that future biorefineries will process lignocellulosic feed stocks and will derive their utilities from renewable resources. Both of these factors lead to higher capital intensity. The risk for an nth plant will be easy to quantify; new facilities will be justified provided the financial returns are adequate. However, high capital intensity will slow adoption of advanced biorefinery concepts.

Acknowledgments

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