doubtedly be required at extra cost if large quantities are to be guaranteed. A recent test of a hay cuber with a new type of die appears to offer the possibility of making dense cubes of rice straw and other cereal crop straws without the need for expensive binder materials. This could be a real breakthrough. More testing of a sustained nature is required to determine maintenance problems and costs.

Orchard prunings may require equipment like that which might be used in the forest slash recovery systems. As in the case of rice straw, this could extend the operating season for portable chippers, hogs, or hammermills. Such equipment could work in the forests and foothill brushlands in the summer and desert brushlands and orchard brush management during the winter, when logging typically is reduced, if not stopped completely. A recent test of two tub grinders originally designed for hay and straw indicates a potential for this type of machine in orchard, forest slash, and brush utilization. A prototype windrow pickup and chipper system has been developed in Delano, California, and is currently being tested for this purpose. Other units are under study and development at other locations throughout the United States.

Costs have been developed on a theoretical basis for baling straw-type biomass; they currently range from $25 to $40 per ton delivered 25 miles from the point of production, not including profits. Orchard prunings, brush, and forest slash could be hammermilled and delivered for about $20 to $30 per ton, also not including profits.

To date these costs have been too high, and no ready markets have been found. Alcohol production could be a major market. It is also not clear who is to bear the costs or portion of costs if the material is not competitive with other fuel or feed stocks. Certainly, cellulosic biomass can compete with electrical energy and Middle Eastern or Alaskan oil. As a renewable energy source and with the benefits to air quality when compared with open field burning, it may make economic sense in some applications, later, if not at this time. We need a few more technological breakthroughs and economic feasibility studies on extended runs with the new collection and densification methods and then some stable economic markets for the products. We have some serious hurdles to get over yet, but they are becoming fewer and not quite as high as they have been, with the rapidly increasing costs of energy and fiber.

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Energy analysis for ethanol

John M. Krochta

A major question in the production and use of fuel-grade ethanol is whether or not it yields a net energy gain after accounting for the fossil energy input required for biomass production, harvesting, transportation, and conversion. Two recent studies concluded that a net energy loss resulted in industrial-grade ethanol production from corn. Use of fossil fuel was assumed for all energy inputs.

We have extended the effort made by these previous studies to include the effects of biomass raw material, production area, process efficiency, ethanol product, by-products, and use of nonfossil fuels for processing.

Biomass raw material

Ethanol can be produced from a wide range of feedstocks based on sugar, starch, or cellulose; sugar and starch feedstocks are the most widely used. Corn, grain sorghum, wheat, potatoes, sugarbeets, sugarcane, and molasses are commonly considered for fermentation to ethanol, and work is under way to improve the efficiency of ethanol production from cellulosic residue feedstocks, such as corn stover and sugarcane bagasse.

The energy input to produce these raw materials varies between 13 and 90 percent of the energy content of a gallon of alcohol, depending on the crop, growing region, and cultural practices used. In addition, the energy input for biomass raw materials such as molasses and corn stover depends very much on agreed-upon accounting methods. Some have argued that both materials should be regarded as waste residues and, therefore, not subject to an energy input accounting. However, because molasses is marketed as an animal feed, a production energy input has been calculated based on the energy required to replace it with another feed material, such as corn. For materials like corn stover, only collection and transportation have been included.

Converting biomass to ethanol

When using grains like corn, grain sorghum, or wheat for feedstock, preparation for fermentation involves enzyme propagation for starch breakdown to fermentable sugars, yeast propagation for fermentation of the sugars to ethanol, grain grinding to expose starch, and grain cooking and enzyme addition to convert the starch to sugars. The grinding and cooking steps for potatoes vary from those of grains because of the potatoes' size and moisture content, but they require a similar preparation energy input.

Using sugarbeets or sugarcane for feedstock eliminates the need to convert starch to sugar. However, other steps are required to produce the sugar juice for fermentation. The preparation energy input for these steps is probably quite close to that for grains.

Molasses, which is approximately 50 percent sugar, only has to be diluted before being fed to the fermentor. Thus, essentially no preparation energy is required.

The preparation energy required to convert the cellulose contents of residues like corn stalks to fermentable sugar has not been well established. Besides cellulose, such materials contain enough hemicellulose and lignin to yield products with energy contents equal to that of the ethanol derived from cellulose. One suggested approach for separating the cellulose, hemicellulose, and lignin from each other involves several preparation steps: (1) chopping the residue material to small particle size; (2) dissolution and hydrolysis of the hemicellulose with a warm alkaline or dilute acid solution to pentoses; (3) dissolution of the crystalline cellulose from lignin with an appropriate solvent; followed by (4) precipitation of the cellulose in an amorphous, exposed form; and (5) hydrolysis by acid or enzymes to glucose. The pentoses can be fermented or converted to useful chemicals such as furfural, while the glucose is fermented to ethanol. The energy input for this longer, more complex preparation is estimated to be two to four times that for grain preparation.

The fermentation step to produce ethanol consumes very little energy, and no energy input is charged to it here. In the case of a cellulosic residue feedstock, the hemicellulose hydrolyzate (mainly pentose) is also converted to useful chemicals. The input energy for this operation is also assumed to be small.

Distillation consumes the most energy of the ethanol production process. The fermented mixture, which consists of approximately 10 percent ethanol along with unfermented, dissolved and undissolved solids, is distilled in a series of steps. The ethanol is first concentrated to 50 percent in a beer still, which leaves behind the unfermented solids in water. The 50 percent ethanol solution is fed to one or more distillation columns, where the ethanol is concentrated to 95 percent (190 proof). If high-quality industrial-grade ethanol is desired, aldehydes and fusel oil are removed. Although some controversy apparently still exists, most researchers claim that these impurities can remain in fuel-grade ethanol, reducing the energy input for distillation.

Production of anhydrous (200 proof) ethanol involves breaking the 95 percent ethanol-water mixture by adding a compound such as benzene in an extractive distillation process. The resulting product can be of industrial or fuel grade, depending on whether impurities were removed in the earlier distillation columns.

The energy input attributed to distillation depends on the type of product desired (95 percent industrial grade, 100 percent fuel grade, or 100 percent industrial grade) and the use of energy-saving techniques. The latter require higher initial capital investment to achieve lower energy consumption and operating costs: optimum distillation design (increased number of stages and minimum reflux ratio) and extensive heat-recovery systems that allow exhange of heat from hot column-exit streams to cold column- and evaporator-inlet streams.

The recent U.S. Department of Agriculture loan-guarantee program for industrial hydrocarbons and alcohols pilot projects included a requirement that the energy content of products and by-products from each project exceed the total energy input from fossil fuels. Several well-known engineering firms have estimated that the energy input for distillation can be cut to 30,000 Btu per gallon of ethanol, or less, for *200-proof fuel-grade ethanol*. Energy input values of 30,000 and 45,000 Btu per gallon to distill 190- and 200-proof industrial-grade ethanol, respectively, are probably achievable.

Where a cellulosic residue is used as a feedstock, a second distillation system is necessary to concentrate and purify the product manufactured from the hydrolyzed hemicellulose fraction of the cellulose. The energy input for this system is likely to be similar to that for producing the 200-proof fuel-grade ethanol.

By-product recovery—concentration and drying—for grain, potato, and sugarbeet feedstocks requires substantially less energy input than the energy value for the by-product as an animal feed. The energy input value for concentration and drying of the distillers grains for corn is based on claims for energy-efficient operations made by applicants in the loan-guarantee program mentioned earlier. Energy-saving measures such as heat recovery from streams leaving the distillation columns and vapor recompression evaporation were utilized. The concentration/drying energy inputs and the feed energy values for sorghum, wheat, potato, and sugarbeet by-products were determined as proportional to those for corn based on their relative weights.

The fermentation by-products obtained when sugarcane juice, molasses, or residues are the feedstocks have not been well characterized, and no fermentation by-product concentration or feed values are listed. At the very least they should have use for fertilization and irrigation. However, the lignin by-product from use of a cellulosic residue feedstock must be dried for sale. Assuming a cellulose:hemicellulose:lignin ratio of 2:2:1 in the original residue feedstock, approximately 7 pounds of lignin will be generated per gallon of ethanol produced. If the lignin can be dewatered to 50 percent moisture, approximately 15,000 Btu will be required for drying. Thus, this value is charged to by-product recovery.

The by-product from the grains, sugarbeets, and potatoes could be dewatered mechanically and used in wet form in local feedlots. Some of the feed value would be lost in the waste water, which could be used for fertilization and irrigation. However, considerable energy savings would result from elimination of the concentration and drying steps.

Overall energy balance

In summarizing the energy input and output data, inputs of 15,000 and 10,000 Btu per gallon of ethanol are included for miscellaneous steam consumption and electrical equipment. These represent a reduction in energy input estimates consistent with those achievable in distillation and by-product recovery. These values have been doubled for residue feedstocks, because considerably more operations are required in this case.

Use of more energy-efficient conversion steps raises the energy output-to-input ratio from previous estimates of 0.6 to 0.8 to our present range of 0.8 to 1.1 for grains. Thus, in areas where grain can be grown most efficiently, at least a break-even energy situa-

TABLE 1. Overall Energy Balance for Production of Fuel-grade, Anhydrous Ethanol from Various Biomass

	Energy							
	Corn	Sorghum	Wheat	Potatoes	Sugar-beets	Sugar-cane	Molasses	Residues
Inputs	*1,000 Btu/gal. ethanol*							
Crop production	33-65	38-76	29-64	19-69	21-41	11-31	33-65	0
Feedstock preparation	9	9	9	9	9	9	0	18-36
Fermentation	0	0	0	0	0	0	0	0
Distillation	30	30	30	30	30	30	30	60*
By-product recovery	30	30	37	12	39	0	0	15
Miscellaneous	15	15	15	15	15	15	15	30
Electricity	10	10	10	10	10	10	10	20
Total	127-159	132-170	130-165	95-145	124-144	75-95	88-120	143-161
Outputs								
Ethanol	84	84	84	84	84	84	84	84
By-products	50	50	62	20	65	0	0	168†
Total	134	134	146	104	149	84	84	252
Outputs/inputs	0.8-1.1	0.8-1.0	0.9-1.1	0.7-1.1	1.0-1.2	0.9-1.1	0.7-0.9	1.6-1.8

*Distillation of ethanol and pentose-conversion product.
†Includes pentose-conversion and lignin products.

TABLE 2. Energy Balance for Production of Fuel-grade, Anhydrous Ethanol with Utilization of Agricultural Residues to Produce Process Steam

Feedstock	Residue	Energy output/Fossil energy input
Corn	Stalks, husks, and cobs	1.8-3.1
Sugarcane	Bagasse	2.0-4.0
Molasses	Bagasse	1.1-2.0

tion exists for converting the grain to anhydrous, fuel-grade ethanol.

Use of potatoes, sugarbeets, sugarcane, or molasses also results in energy output-to-input ratios quite close to 1.0. Characterization and utilization of the fermentation by-product from sugarcane and molasses will probably improve their energy ratios. Additional energy-saving innovations, including use of feed by-products in wet form increases the energy ratio to 1.0 to 1.5 for the grains, potatoes, and sugarbeets.

The most favorable energy balance occurs with use of cellulosic residue as the feedstock, largely because no energy is charged for crop production and because usable by-products are obtained from the hemicellulose and lignin. With the attractive energy balance feature of this approach, commercialization will depend on adequate pilot-scale demonstration and economic feasibility.

Since it is fossil energy input that is critical and, thus, counted in the energy balance for ethanol production from biomass, any use of renewable, nonfossil fuel would improve the energy balance. Other researchers have shown that recovering 50 percent of the corn field residue (stalks, cobs, and husks) for their energy value could supply a conversion energy input of 83,000 Btu per gallon of ethanol produced. If this practice could be made economically feasible for year-round operation, and if soil quality were not affected, use of corn field residues would improve the ethanol energy balance considerably. Based on our analysis, 50 percent of field residue could supply the energy requirement for feedstock preparation, distillation, by-product recovery, and miscellaneous. Thus, the ratio of energy output to input (fossil) for corn would increase to a range of 1.8 to 3.1.

Sugarcane juice or molasses as the feedstock would provide the opportunity to use sugarcane bagasse for fuel. In normal processing of sugarcane to refined sugar, sufficient bagasse is available to produce steam for a plant to convert the molasses to ethanol. For the time bagasse is available to provide steam for a molasses-to-ethanol plant, the energy output-to-input (fossil) ratio would be 1.1 to 2.0. If the sugarcane were used directly to produce ethanol via sugar juice, the bagasse could provide enough steam for the conversion process. Thus, the energy output to input (fossil) ratio would increase to 2.0 to 4.0.

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Crop feedstocks for fuel alcohol production

Roy M. Sachs

Ethyl alcohol is now produced in the United States by fermentation of high-starch-containing crops, foremost among which are the cereal grains and especially corn. Other good sources are potato, sweet potato, yam, Jerusalem artichoke, and cassava (used in Brazil). Sugarcane, sugarbeet, sweet sorghum, and fodder beet (mangold) give higher alcohol yields per acre than the starch crops, but grains have been the main source of alcohol.

Alcohol itself may be regarded as a by-product. The "food and fuel" concept is predicated on the fact that the overall nutritional value of crops is improved even as their carbohydrate content is reduced in the fermentation process. Most of our corn, many other grains, and many crop by-products are used for animal feed. When the bulk of the readily digested carbohydrates are removed from the grains, the residual spent grain, with increased protein concentration and other benefits derived from the yeast organism, finds it way into the feed market at prices almost equal to those of high-protein seed meals. Carbohydrate supplements to animal feeds are then derived from lower priced hay or forage crops. Malt and yeast supplements also work well in human nutrition, and brewer's spent grains may find use in breads and other products.

The crops

Almost all yield data in this presentation come from the California Crop and Livestock Reporting Service. These are average yields for 1978; they are well below those which many growers achieve and below those used by many analyses for biomass-to-fuel computations.

The data for Jerusalem artichoke, fodder beet, and sweet sorghum are from small-scale trials in Canada, New Zealand, and Texas/Louisiana, respectively; they should be compared, in all justice, with high-value data for other crops grown under similar conditions. The high values for fodder beet do not seem unreasonable, even though we have little information on the inputs required to obtain these yields. They are the averages for nonirrigated trials with 20 different cultivars, and one expects the yields to be significantly greater with irrigation. Four small irrigated plots of Jerusalem artichoke in Davis have yielded as much as 33 tons per acre (average 26.5 tons per acre) of tubers in about 110 days with a July 1 planting date. We expect to obtain higher yields with an earlier planting date.

Ideally, economic analyses and decisions concerning complex agricultural-industrial systems, as represented by crops to fuel alcohol, should be made from systems in operation and not merely from computations found in this article. Currently fuel-grade, fermentation ethanol sells for about $1.75 per gallon in the United States. The computed costs in table 3 are considerably below this value and, hence, must be examined closely in systems in operation. Such important data were not available to the author at the time of manuscript preparation, and interested readers are urged to inquire further.

Among the widely grown crops in California, the sugarbeet has by far the best potential alcohol yield—600 to 700 gallons per acre. Irish potatoes and corn follow at 400 and 360 gallons per acre, respectively. Grain sorghum may yield much more in some areas and would then be competitive with corn. The alcohol yields were computed by assuming that 13.6 pounds of fermentable materials will yield 1 gallon of alcohol (147 gallons per ton fermentables), a yield used by the Battelle Institute, a private research organization in Columbus, Ohio, and somewhat higher than that used by the U.S. Department of Agriculture and other laboratories.

If sweet sorghum were introduced into California, it could make a strong, perhaps the best, contribution to fuel alcohol production. Most varieties are quick crops, maturing in 110 to 130 days in Texas and Louisiana, and would presumably perform equally well in many California locations. The alcohol yield of nearly 500 gallons per