Fuels from Biomass: Integration with Food and Materials Systems

Adaptive biomass systems make multiple outputs available in response to demand changes.

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Biomass is a renewable resource capable of providing nonpolluting, safe fuels. Usually, biomass could alternatively be the source of food, materials, or chemicals. Even when the biomass is useful only for fuel, the same factors of production (such as land and water) could be used to produce food, animal feed, textiles, paper, construction products, or chemicals. The question is whether there are enough of the factors of production to go around.

Summary. The development of fuels from biomass can lead naturally to dispersed facilities that incorporate food or materials production (or both) with fuel production, forming adaptive systems that can be modified to meet evolving needs and constraints. The technology that is appropriate to each system needs to be worked out, taking into account associated food and materials opportunities in order to decrease the ultimate cost of energy delivered to the consumer. I analyze possible systems based on sugarcane, corn, and guayule.

The purpose of this article is to present some means of integrating the production of fuels from biomass with the production of food and materials, to form adaptive systems. Adaptive systems modify themselves to meet evolving needs and constraints (*1*). These systems contrast with two alternatives: the energy farm and the use of agricultural residues. Either the energy farm concept or the residue approach can evolve into an adaptive system.

The energy farm concept has been analyzed, especially for short rotation forestry (*2*). The output of the energy farm can be used directly as a fuel or indirectly in the production of energy-intensive chemicals. It is processed at a central conversion facility. The farm depends on high yield, frequently obtained by coppicing (regrowing plants from stumps), fertilizing, and irrigating.

At 25 tons per hectare (dry weight basis), almost 3 million hectares are required for a woody biomass crop to produce 1 quad of energy, when the moisture content of the fuel is taken into account (*3*). The Department of Energy's biomass cost target is $0.95 to $1.40 per gigajoule (GJ) (*4*). At this cost, the revenue of the energy farm would have to be only $400 to $560 per hectare, which is little for intensive silviculture. There are good prospects for attaining the high yields needed when cost is not a factor (*5*). The cost target of $400 per hectare probably can be attained, but only at the sacrifice of high yield. Therefore, at least part of the energy farm output must be sold at prices higher than the $0.95 to $1.40 per GJ. The ability to meet the cost targets will remain in doubt for almost a decade, because many years are required to determine the economics of a new forestry system. This is especially true because low cost is a function of the successful coppicing (*6*) of multiple crops, and selection of appropriate tree species.

The agricultural residue approach avoids the high capital and operating costs (obstacles for the energy farm) only at the sacrifice of quantity and complete dedication of the biomass to fuel production. It is rare that residue concentration exceeds 7 dry metric tons per hectare (*7*). The corn stover residues from approximately half of the present crop (or about 13 million hectares) would be required for one quad of energy content. It would be deleterious to the soil to remove more than about half of the residues. Furthermore, once 50 million or more tons of corn stover are mobilized by the adoption of new harvesting, collection, and transportation systems, active competitors for purchase of the residue for food, feed, or materials use may appear.

The concepts of the energy farm, the integrated system, and the residue system blend into each other. An energy farm manager may find that pulpwood prices are high enough to make it profitable to divert part of his chips to the pulp and paper industry. By doing this, he could reduce the unit cost of the remaining biomass. A biomass conversion facility that manufactures steam and electric power may improve its profitability position by establishing facilities that use the steam that otherwise would be suboptimally used or wasted. These facilities could be for the manufacture of materials, such as particleboard or furfural. Thus, normal cost and profit pressures would tend to cause energy farms to become parts of integrated systems.

Agricultural residue systems might evolve into integrated systems for similar cost and profit reasons. Residue biomass conversion facilities would have to offer sufficient payment to farmers when adverse weather or market conditions might reduce residue shipments. The mobilization of residues probably would lead to active competition with the biomass-to-fuels conversion facility.

Systems Flow

Conventional agriculture and silviculture have placed biomass systems in constraints that must be removed if significant fuel production is to result. Before discussing specific opportunities to integrate fuel production with food and materials systems, it is worthwhile to consider the flow of materials in a hypothetical biomass system (Fig. 1) in which steps are taken to integrate fuel production into food or materials systems. The "farm" may be either terrestrial or aquatic. Agronomic practices, such as close spacing (*8*), coppicing, ratooning, and multiple cropping are used to increase yields and thus reduce unit biomass costs. Periodically, separation processes take place on the farm. These

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include harvesting, the return of selected plant parts to the soil, and the preparation of other plant parts for temporary storage. The separation processes yield primary farm outputs that are transported to central processing facilities. Other, incidental outputs include roots that are left in the ground, leaves and "trash" that are left as field residues, and other residues that remain on the farm. These incidental outputs may be collected and used for livestock feeding, soil improvement, or energy production.

At the central processing facility, the primary factory inputs are separated from those that arrive only incidentally. For example, logs or woodchips are debarked prior to the manufacture of lumber or paper pulp. Bark becomes an incidental factory output. The primary factory input (logs or wood chips) then is subjected to conversion processes to manufacture salable products, which are stored and transported to appropriate markets.

The incidental factory outputs, resulting from the separation processes, and incidental conversion outputs may be of such little value that they are subjected to disposal. Additional conversion processes may upgrade these outputs either to salable products or to products suitable for use at the factory. For example, lignocellulosic residues might be used at a factory to generate process steam and electricity.

The most obvious strategy for seeking fuels-from-biomass opportunities is to examine each incidental output to determine its suitability for manufacture of fuels. Significant quantities of inexpensive fuels can be produced by an astute selection of biomass crop, conversion processes, and end-use markets. The food or materials producer might benefit from reduced disposal costs, increased reliability in energy supply, and possible revenue from outside sales. Another, more powerful, strategy is a flexible coproduct manufacturing system in which key biomass intermediates are processed either into fuels or materials, depending on relative price levels. Application of this strategy to sugarcane is illustrated in Fig. 2. When the price of crystalline sugar is satisfactory, only the molasses by-product of sugar manufacture would be converted to ethanol. When sugar prices are low substantial quantities of sugarcane juice could be diverted to the production of ethanol (*9*). The reduced sugar inventories could quickly lead to sugar price recovery. The feasibility and attractiveness of this strategy depends on having flexible fermentation facilities, and a willingness to suffer the economic consequences of leaving the fermentation facilities idle when sugar prices are high. For sugar crops, molasses is a stable, concentrated, storable material. Therefore, during bad times, sugarcane juice could be fermented during the sugarcane harvesting season and stored molasses could be fermented during the off-season. Thus, the facility would operate for a variable number of days per year, depending on market conditions.

Objectives

Biomass-to-energy systems are of three major types (Fig. 3): (i) direct combustion of biomass materials, generally to manufacture process heat, steam, or electricity; (ii) the manufacture of molecules that are rich in carbon or hydrogen (or both) and poor in those elements (such as oxygen and nitrogen) that do not contribute to high energy content; and (iii) feeding of biomass to work animals. The first two approaches are significant. The first approach requires engineering ingenuity in order to obtain low moisture biomass boiler feed and to conduct direct combustion efficiently. The second approach is of greatest scientific interest. The low efficiency and adverse environmental impact of animals as a source of power removes the third alternative from serious consideration at this time in the United States.

The widespread use of petroleum, natural gas, and coal as sources of fuel arises from their high energy content. The high energy content in turn arises from their chemical composition which generally is low in oxygen, nitrogen, and inorganic matter. Their major chemical constituents are carbon and hydrogen, which burn readily, liberating heat that can be used to perform work or to adjust the temperature in an environment.

Some species of plants manufacture

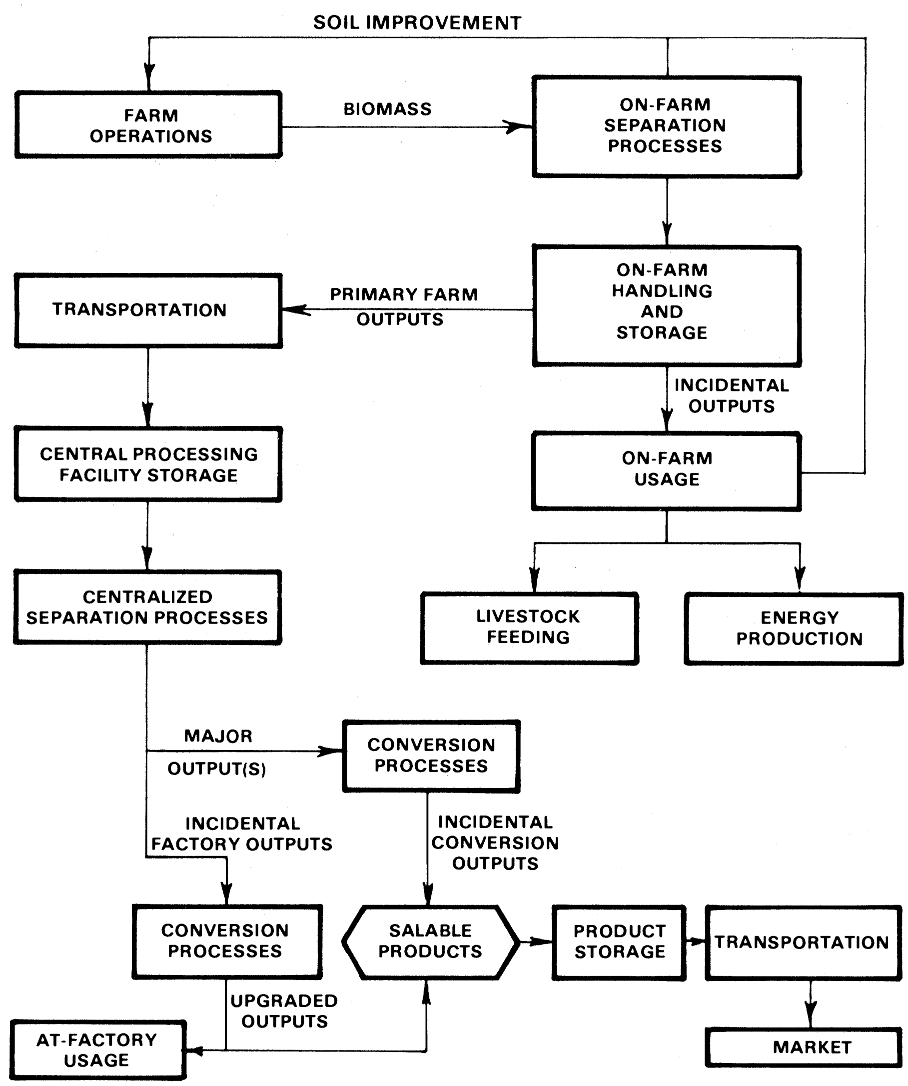

Fig. 1. Systems flow in biomass production and conversion.

Table 1. Comparison of heats of combustion of biomass constituents, fuels from biomass, and fossil fuels. Values for heat of combustion are approximate.

Heat of combustion (gigajoules/ metric ton)	Biomass constituents	Fuels from biomass	Fossil fuels
50		Methane	Natural gas
45			
40	Turpentine	Butanol	Gasoline
35	Triglyceride oils ~ steroids ~ lignin		Fuel oil > bituminous coals
30		Acetone > ethanol	
25			
20		Furfural > methanol	
15	Wood > starch ~ cellulose > sucrose > glucose		
10		Acetic acid	

energy-rich chemicals by various biosynthetic pathways. This biosynthesis frequently goes through intermediates such as glucose that have as many oxygen atoms as carbon atoms (Table 1). Carbohydrates are inherently low in energy (14 GJ per ton). Storage carbohydrates such as starch have the formula $[C_6H_{10}O_5]_n$ which has a slightly higher energy value (15.4 GJ per ton) due to the loss of a molecule of water from each glucose unit. Cellulose is energetically about the same as starch for all practical purposes. Lignin has a considerably higher energy content than the carbohydrates because (i) many oxygen atoms have been lost from the glucose molecules from which lignin is formed and (ii) energy-rich aromatic structures have been formed (*10*). Lipids, terpenoids, and steroids are manufactured biosynthetically from acetate by means of various secondary metabolic processes (*10*). These products are used primarily for food and pharmaceuticals now, but they are possible fuel sources.

When biomass is subjected to microbiological or thermal conversion, end products can be formed that have more energy content than does the biomass starting material. The additional energy per unit weight arises from loss of oxygen, carbon dioxide, formation of energy-rich carbon-carbon double bonds, or formation of energy-rich ring structures. The energy content of the major candidate fuel products derived from biomass have higher energy contents than do sugars, starch, and cellulose but are no higher and in many instances are considerably lower in energy content than are lipids and terpenoids. In some instances, the advantages in energy content may be small but the liquid or gaseous fuel may be more convenient to transport and store than the biomass starting material would be.

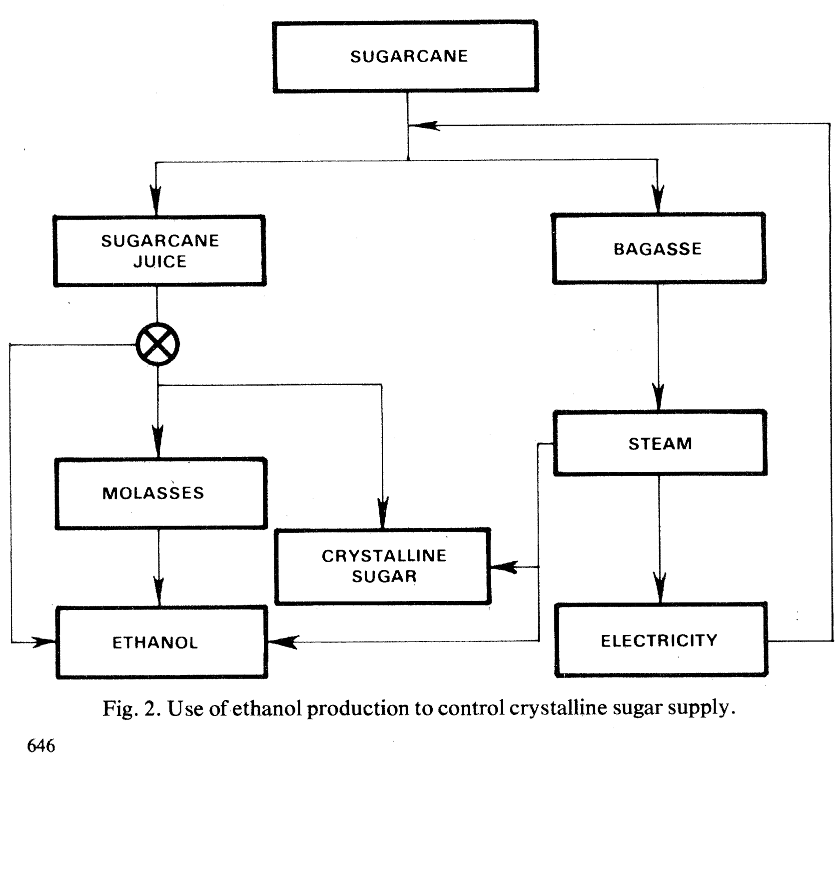

Fig. 2. Use of ethanol production to control crystalline sugar supply.

Corn-Based Fuels

Whenever corn or other grains are suggested as sources of fuels, the argument is advanced that conversion of corn grain into fuel is undesirable because it could cause a food shortage (*11*). However, it is at least theoretically possible to reorganize the present U.S. corn biomass system to permit production of 10 billion to 18 billion liters of ethanol (or its equivalent in other fermentation products) while obtaining the same quantity of end-use food products, in the form of beef, poultry, and pork, of a quality equal or superior to present standards. Ten billion liters of ethanol could be used as an antiknock fuel ingredient for approximately 20 to 25 percent of U.S. gasoline, assuming a 10 percent blend with gasoline. This increase in outputs could be achieved without increasing the land area devoted to corn or increasing the yield of corn above that obtained now. Such a change might appear miraculous but is actually based on three simple facts: (i) cattle and other ruminant animals are capable of digesting polysaccharides that are indigestible to nonruminant animals; (ii) corn stover (stalks, cobs, husks, and leaves of the corn plant), which is rich in these polysaccharides that are digestible by cattle, is underutilized now; and (iii) U.S. production of corn stover could provide ample replacement for the corn grain now fed to cattle. Briefly, the concept is to manufacture ethanol and a protein-rich stillage from some of the grain now used to feed ruminant animals in the United States. Figure 4 shows both the present and suggested corn biomass systems along with the valves to adjust product flows. An amount of corn stover equivalent to the grain used for ethanol would be harvested from the cornfields at a rate that does not endanger the soil. The quantity that could be diverted depends on the latitude, terrain, and soil type of each specific cornfield. The stover and the stillage would be fed to cattle so that the same quantity of beef would be obtained. The digestibility of corn stover presently is less than grain, hence the equivalence may be 2 tons of stover per ton of grain diverted (*12*). The U.S. production of stover is ample to supply the needed tonnage. The use of corn grain by nonruminant animals (poultry and hogs) would continue at the present rate, as would industrial conversion of corn into starch and other products.

Approximately 1.7 billion bushels of corn grain are dedicated to domestic cattle feed (*13*). Corn grain is used now because it is highly digestible, relatively cheap, and yields a marbelized effect needed to attain the high meat inspection grades (*14*). Also, corn grain supplies some of the nitrogen compounds from which the ruminant animal manufactures its protein.

The density, size, shape, and waxy outer layer of corn grain make it relatively simple and cheap to transport and to store. When dried properly and stored in a suitable environment, corn grain is stable for years. In contrast, corn stover is low in density, is obtained at a much higher moisture level than is corn grain, and is relatively unstable. Transporting corn stover over long distances to central locations where large-scale conversion could take place over extended processing seasons appears tenuous.

If cattle were fed corn stover locally during the seasons of the year in which it is abundant, some major objections to the use of corn stover could be overcome. The protein not obtained from corn stover would be supplied indirectly from grain or from the stillage.

Researchers at Purdue University have announced a major breakthrough in the treatment of corn stover to obtain simple sugars for fermentation to ethanol (*15*). An organic acid treatment facilitates the attack of fungal cellulases on lignocellulose. The probability that this process could increase the digestibility of corn stover by cattle is high because the low digestibility arises from crystalline cellulose or cellulose protected by lignin (*16*). Although details of the Purdue process are lacking at this time, it is likely that the same treatment that renders cellulose susceptible to cellulases derived from the fungus *Trichoderma viride* could make the cellulose susceptible to the enzymes present in the cattle rumen. If so, the digestibility of corn stover could rise from about 45 to 70 percent or more.

The stover, with or without pretreatment, would not replace all of the corn grain. Time is money in a modern feedlot and cattle reach market weight faster if they are finished on corn grain.

This suggestion illustrates the interaction of the food and fuels systems to the benefit of all concerned. The corn farmer who previously sold perhaps 250 bushels of corn per hectare at $2 per bushel ($80 per metric ton) and who received no cash for his stover now could expect perhaps $30 to $40 per ton ($80 to $120 per hectare) for his stover, in addition to his corn grain revenue. The cattle producer could hope to use less than 2 tons of stover to replace 1 ton of grain, if the pretreatment were successful. Thus, both the corn farmer and the cattle feeder improve their positions. The ethanol producer would have access to grain that is easy to convert to ethanol or other fermentation-derived fuel. He would not have to deal with the technical uncertainties of the cellulose-to-glucose route. There is a ready market in cattle production for the stillage by-product of the fermentation. Fuel producers could purchase ethanol for antiknock and fuel use, thus reducing petroleum imports.

The skeptic could claim that in times of dire need for food and feed grains the price of corn grain would rise above what the ethanol producer could afford to pay, while the corn is exported in huge quantities. But the suggested system increases the overall biomass resources of the United States. In this situation, the balance of payments and farm income could be raised. The stover cannot be shipped overseas and it would become the U.S. beef consumers' guarantee that beef supplies could remain relatively plentiful.

Impact of a New Process

The traditional means of processing conventional crops frequently inhibits production of fuels and chemicals from biomass at attractively low costs. For example, the present milling system for sugarcane results in fermentable sugars (sucrose, fructose, and glucose) at a cost of about $0.132 per kilogram on a dry weight basis (*17*). At this cost level for sugarcane-derived fermentable sugars, ethanol is likely to cost approximately $0.30 per liter (*18*). At $0.30 per liter, industrial applications for ethanol can be tapped, but for substantial penetration of motor fuel markets a lower ethanol selling price is required.

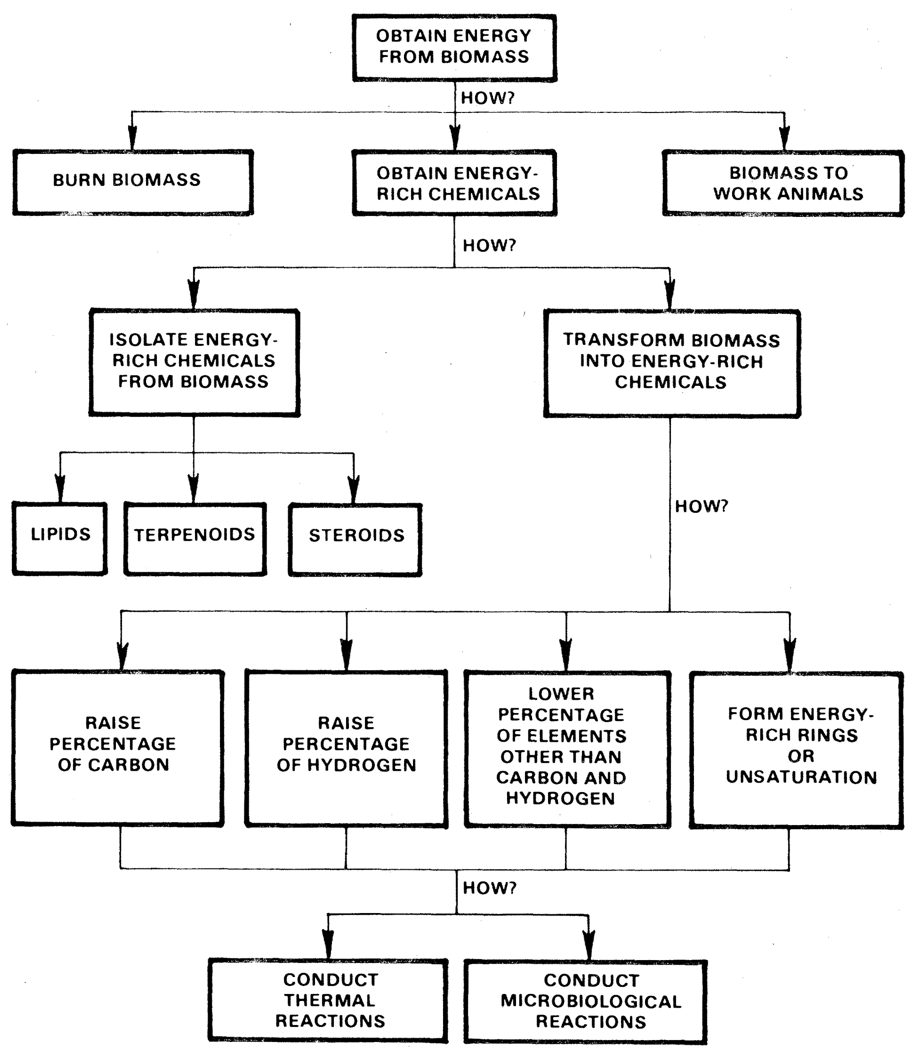

Fig. 3. Alternatives to obtain energy from biomass.

Reduction in the cost of ethanol derived from sugarcane can arise by four approaches. Only one of these four methods is within the major scope of this article but the others are mentioned for the sake of completeness. The cost of the sugarcane delivered to the processing facility can be reduced by increasing the yield of sugarcane without increasing the cost proportionately. The most active and promising yield-increasing research now in progress is the use of narrow row spacings (approximately 0.6 meter instead of 1.83 meters) to increase substantially the plant population and to achieve canopy closure at an early date (*19*). A second method of reducing ethanol costs is to reduce the cost of fermentation process. However, fermentation is a relatively minor factor in the cost of ethanol. Raw materials account for approximately $0.20 of the $0.30 per liter and much of the remainder is provision for profits, taxes, and other capital charges. The third method to reduce ethanol cost is to reduce the processing cost in making sugarcane juice from sugarcane. These costs have been shown to be virtually negligible, compared with the agricultural costs of sugarcane delivered to the mill (*20*).

The fourth approach is modification of the sugarcane process so that coproduct credits reduce the net cost of fermentable sugars. The cost of sugarcane delivered to a processing facility is approximately $66 per metric ton on a dry weight basis. Roughly half of the sugarcane is fermentable sugars; the rest is a lignocellulosic material that presently has a fuel value of $26 per ton or less (*20*). The present sugarcane milling procedure leads to a relatively dilute solution of sugar that requires evaporation and crystallization to obtain a salable product. The sugarcane stalk consists of a soft central core or pith which has over 90 percent of the fermentable sugars, a tough rind, and a waxy epidermis. In the process of removing the sugars from the millable stalk, the pith and rind (which are largely separate in the intact sugarcane stalk) become crushed and ground together, along with the waxy epidermis and adhering dirt. This "bagasse" is of low quality and has only the fuel value that can be assigned to a product with at least 50 percent moisture.

A new sugarcane process is under development in Canada (*21*) that promises to provide coproducts with higher values (Fig. 5). Briefly, sugarcane is cut into billets 1 foot long, which are cut longitudinally by a knife into two halves. A rotating coring device removes the pith from each half without disturbing the rind fibers. The waxy epidermis and any adhering dirt are scraped off the outside of the cane so that both the rind fibers and the pith are clean. The pith contains approximately 92 percent of the sugars in sugarcane. The sugars can be obtained by alternate squeezing and imbibition with water. When the objective is to make both table sugar and fermentation products at the same location, it may be possible to remove a relatively concentrated sugar solution for table sugar production from the pith with the first squeezing and then use the pith with its adhering sugars and molasses as the fermentable sugars in the ethanol plant.

Although this new process probably reduces the processing cost of fermentable sugars, the major advantage will be in the increased value of the rind fiber. This uninjured fiber is initially in the form of sugarcane segments which can be separated into foot-long strands that can be combined with thermosetting polymers to make simulated lumber or plywood products. The development of these products is at too early a stage at this time to assign a value but it surely will be well above that of fuel.

Conventional sugarcane bagasse is a source of fiber for papermaking, especially in countries that have considerable sugarcane and few pulpwood-type trees. To make paper of relatively high quality, it is necessary to depith the bagasse. Depithing is a relatively expensive process that has inevitable fiber losses associated with it. The new Canadian process generates rind fiber that has already been depithed. Furthermore, the rind fiber has not been injured by the crushing and milling operations. Dr. Joseph Atchison has estimated that the rind fiber may attain a value about double that of conventional bagasse for papermaking (*22*). Therefore, the Canadian process appears to meet one of the major fuels-from-biomass goals, namely the goal of a nonfuel coproduct to generate significant revenues that permit assignment of a lower cost to (in this case) fermentable sugars.

Rind fibers also appear promising as a storable fuel source, which would extend the processing season during which eth-

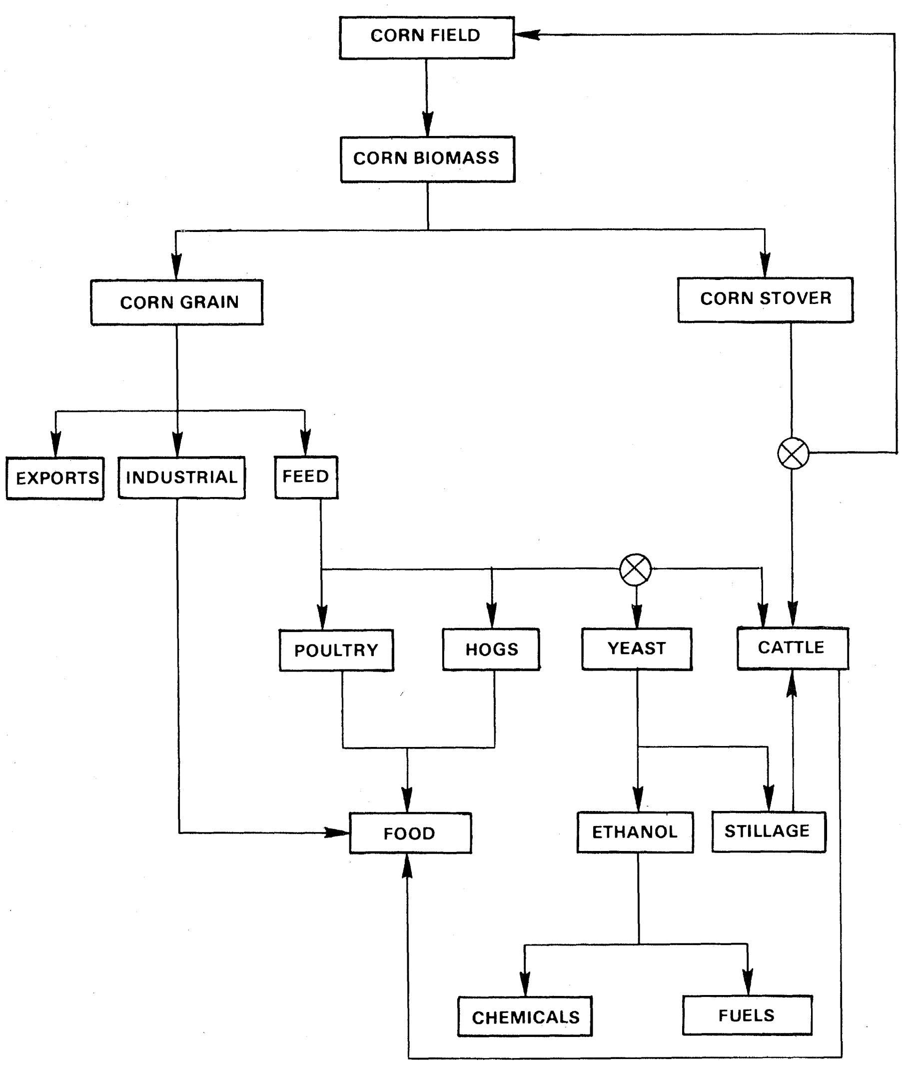

Fig. 4. Hypothetical corn-to-ethanol system, integrated with conventional utilization of corn.

anol can be distilled with fuel generated at the site. After removal of sugars, the lignocellulosic pith remains. If ethanol and stillage are manufactured at the processing facility, the leftover pith can be used to absorb the concentrated stillage to make cattle feed. If the rind fiber is selling well for high-value uses and fossil fuel is scarce, it may be necessary to use the pith as a source of steam and electricity by direct combustion. Ultimately, this finely divided lignocellulosic product would be an excellent substrate for production of simple sugars by enzyme or acid hydrolysis (or both). The achievement of the high surface area that pith has naturally is a costly process for many other substrates. Enzyme hydrolysis at the present state of the art yields relatively dilute solutions, and concentrating these solutions is an important cost factor. In an integrated facility, the enzyme hydrolyzate can be blended with molasses to achieve a satisfactory concentration of fermentable sugars.

The introduction of the Canadian Separator Equipment Process could lead to greatly reduced net fermentable sugars cost. The fact that the millable sugarcane stalk might yield so much salable coproduct that there would be no fiber left to make steam and electricity to run the process is not a serious disadvantage. In the first place, very little power is required to operate this process compared with one that grinds and mills. Second, the harvesting of the entire aerial portion of the sugarcane plant, with return to the soil only of the amount that is needed to ensure soil conservation, probably would lead to the delivery of an additional 20 percent lignocellulosic material to the central processing facility (*20*). This material (tops and leaves) could be dedicated to the generation of steam and electricity for operation of the sugarcane separation and for ethanol distillation processes.

Guayule

The United States is vulnerable to a natural rubber embargo because production is concentrated in Asia, and the United States produces no natural rubber. Despite the development of a 2-million ton synthetic rubber market, natural rubber is still needed for radial tires for passenger automobiles, for aircraft tires, and for truck tires. Furthermore, synthetic rubber uses petroleum feedstocks that are needed for gasoline production. The development of guayule (*23*) as a domestic source of natural rubber could provide opportunities to integrate critical materials production with fuels production (Fig. 6). The natural rubber would be the "bread and butter" product that would be sold to make the agricultural and conversion ventures profitable. The coproduct mixture of terpenoids and lipids is rich in energy and could be processed into liquid fuels. The bagasse could be used to produce steam and electricity to operate the facility and possibly for outside sale. A process under development in Mexico has been described (*23*) but it may not maximize recovery of lipids and terpenoids because emphasis is on the removal of these contaminants from the natural rubber.

Natural rubber sells for approximately $0.40 per pound. Our consumption is approximately 700,000 tons per year and is expected to grow with the increasing demand for radial tires and as it displaces the increasingly expensive synthetic rubber manufactured from petrochemical sources. In assessing the possible impact of a guayule development on fuels-from-biomass, it is desirable to consider, from this source, a domestic natural rubber production of 1 million tons per year.

Published information regarding the detailed composition and yield of resinous coproducts is sketchy, but they are a complex mixture of lipids with mono-, sesqui-, and diterpenes (*24*). The lipids are triglycerides with both saturated and unsaturated fatty acids. To obtain a high quality natural rubber, it is necessary to deresinate the crude product. The resin coproduct content might equal the natural rubber content of guayule under favorable circumstances. Therefore, the expected direct liquid fuel output from guayule would be moderate. The terpenoids and lipids meet two requirements for fuels from biomass feasibility: (i) they are high in energy, having a carbon-to-oxygen ratio of at least 10 to 1; therefore they equal or surpass gasoline in energy content; and (ii) the mixture of chemicals is so complex that a simple fuel-making process is likely to win out over an attempted separation of valuable chemicals.

To make motor fuel from this crude mixture would require conversion of olefinic unsaturation into aromatic-ring compounds or hydrogenated compounds. The lipids would have too high a boiling point for gasoline but might be

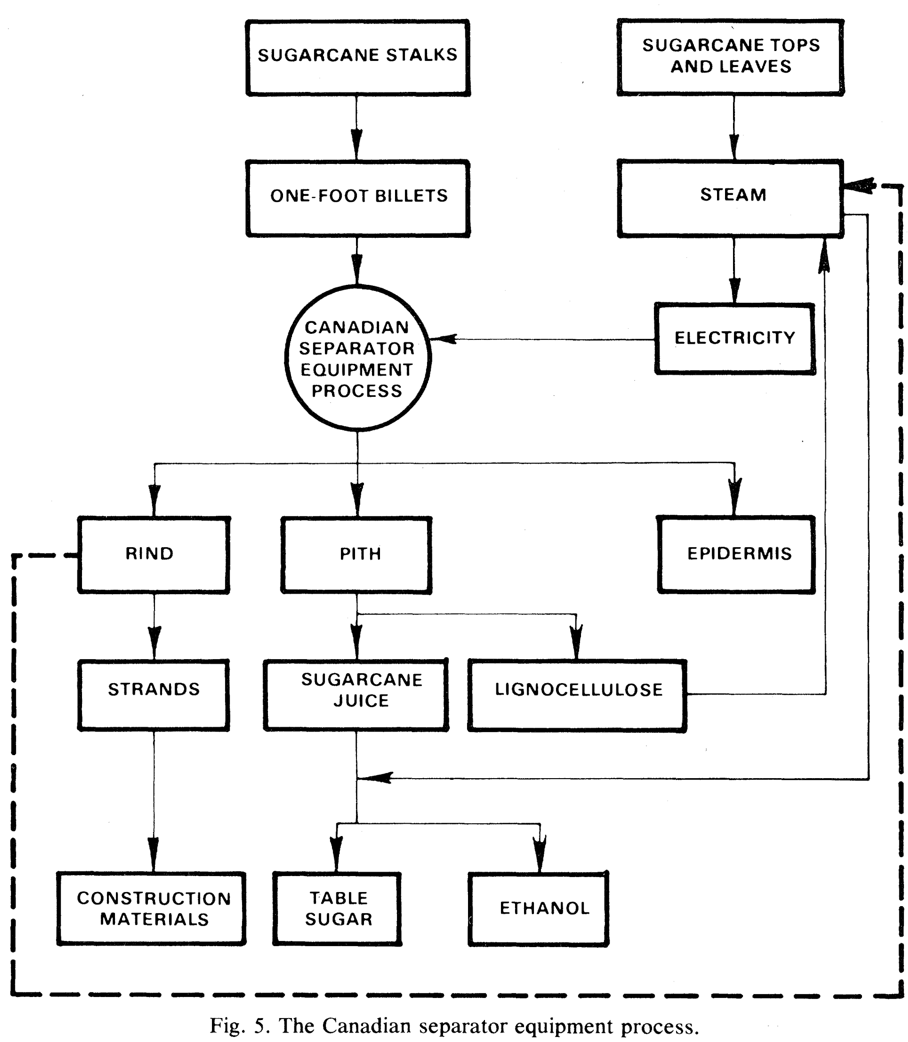

Fig. 5. The Canadian separator equipment process.

converted to diesel fuel. Various approaches to the conversion of such mixtures need to be investigated, not only for guayule but also for the *Euphorbia* species now under study by Calvin *et al.* (*25*).

Policy Implications

The popular press has stressed ethanol as the principal liquid fuel obtainable from biomass but scientists, technologists, and policy-makers need to remain alert to opportunities afforded by other chemicals with higher energy content and potentially lower costs. Terpenes and lipids are two classes of natural products that merit greater attention.

Biomass systems from which variable product mixes of food, materials, and energy can be derived, within changing environmental constraints, are adaptive. The theory of adaptive systems is developing rapidly (*26*). Biomass can and should be used to adapt our resources to concurrent crises in energy, food, materials, and the environment (*27*). The hierarchy of applications for a product or a resource is arranged in an order of displacement based on opportunity cost (*28*). Thus for ethanol, beverage > industrial solvent > chemical intermediate > fuel. These hierarchies act as constraints in the adaptive systems.

A growing forest, the wood from which can become lumber, plywood, pulpwood, or fuel, gives producers and consumers the flexibility needed to survive the multiple future crises that we face (*29*). When the trees are planted, we will not know which uses the forest resource will be put to when it is harvested. To plant trees that are useful only as a fuel represents a suboptimization unless yields far surpass those from multipurpose trees. A restriction of annual crop output to boost prices received by farmers is an archaic notion: grain not needed overseas due to good harvests abroad can be converted to chemicals and fuels.

If or when fuel prices double due to the depletion of fossil fuel supplies, fuels from biomass may possibly supply 10 percent or more of a curtailed U.S. energy consumption. However, in the next 10 to 20 years, the achievement of competitive costs for fuels from biomass would depend primarily on the integration of fuel production with food and materials production. Those engaged in research and development, agriculture, business, and government are challenged to develop not only the know-how but also the know-what, know-where, and know-when, and know-why (*26*). Knowing when and where to switch from emphasis on food and materials to emphasis on fuels is just as important as knowing how to produce the fuels.

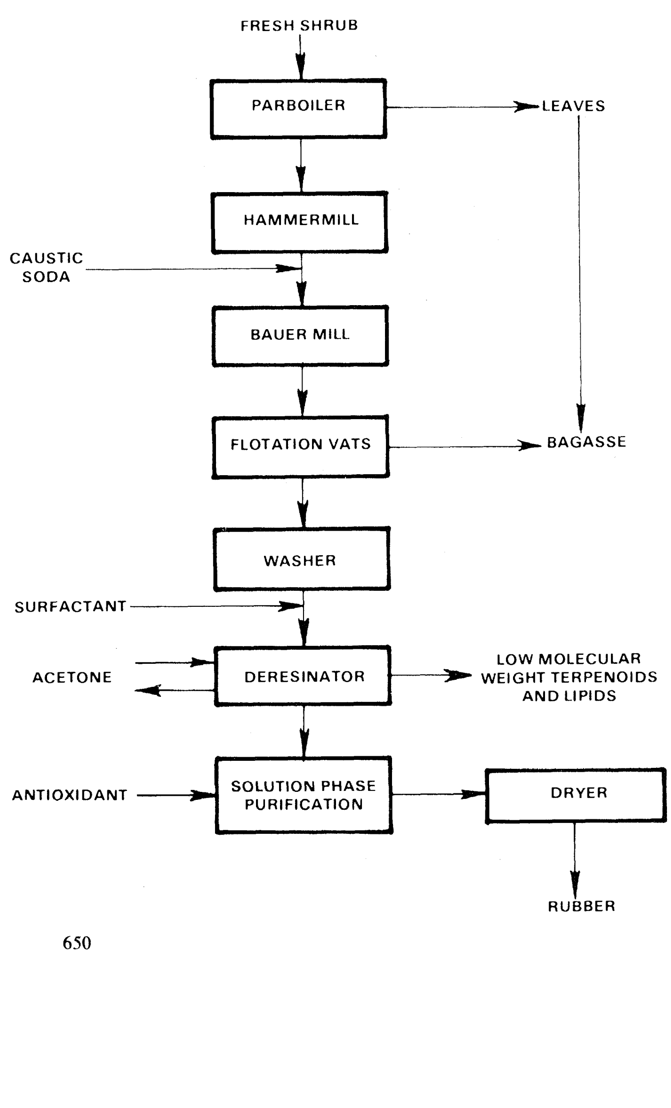

Fig. 6. Mexican process for extraction of rubber from guayule shrubs. Adapted from National Academy of Sciences study.

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Solar Energy for Village Development

Norman L. Brown and James W. Howe

Most of the people in the developing countries of Asia, Africa, and Latin America live in rural areas. Progress in these areas depends on finding substitutes for human muscle energy, which is now relied on for many village tasks.

Summary. The National Academy of Sciences held a joint workshop with the Government of Tanzania last August on the potential of solar energy for the villages of that country. Costs of five solar technologies (mini–hydroelectric generators, wind, methane generation from organic wastes, photovoltaic cells, and flat-plate solar collectors) were compared with costs of diesel-generated electricity and with electricity from the national grid. Each of the five technologies is either now competitive with diesel or will be in a few years. Although the figures presented are not conclusive since they are derived from calculations rather than an actual test, the results are encouraging enough to warrant serious testing in Third World villages.

The prohibitive costs of large central generators and massive transmission and distribution systems, as well as the slow pace of the spread of rural electrification programs, discourage hopes that rural energy needs can be met with a national electric grid. Hence, we have inquired into the potential of small-scale technologies that use renewable energy sources coming from the sun. Current solar energy comes from four major systems: (i) photosynthesis, which is the basis of all life, both plant and animal; (ii) the water cycle, which is driven by the sun; (iii) wind, caused by the atmospheric pressure differences due to changing amounts of solar energy falling on different places; and (iv) direct sunshine. Proven small-scale technologies exist for using each of these solar energy systems.

In photosynthesis, biogas plants use anaerobic bacteria to turn animal, human, and crop wastes into methane gas and, at the same time, leave a residual slurry that is useful for fertilizer. It has been reported that there were 1.2 million biogas plants installed in China in the first 6 months of 1976 alone, and that 4.7 million are now in operation (*1*). The technology appears to be proving itself and is improving all the time. Methane can be used for cooking, crop drying, power generation, and various other purposes.

To make use of the water cycle, a number of very small hydroelectric generators are now being manufactured for as little as $800. Miniature units producing only a few hundred watts or a few kilowatts can operate either with a small dam or simply by the flow of a small stream. In China, it is reported, there are 60,000 such units averaging about 40 kilowatts in capacity that successfully supply most of the electricity used by three-quarters of China's rural communes (*1*, pp. 27 and 28). In the 19th and early 20th centuries, most of New England's commercial power came from small hydrofacilities.

Windmills had long since proved themselves in Holland and the plains of the United States before they were driven out of existence by rural electrification—originally based on coal and later on cheap oil.

At least two small-scale technologies are available to make use of the direct rays of the sun. One is a flat-plate collector for space and water heating but which could also serve for activities such as crop and fish drying, distilling water, and refrigerating. The other technology for collecting the direct rays of the sun to generate electricity is a solar cell or photovoltaic array such as that used to power spacecraft.

Such promising technologies could be useful for a variety of tasks in rural areas. This potential is described in Table 1, where 14 technologies are applied to 15 common village tasks with the result that there are 44 applications that seem useful and 28 applications that seem marginally useful.

But what of costs? Are these not all technologies that require years more of research or the establishment of mass markets to become cost competitive with conventional energy sources? So few good data have been kept on the costs and performance of such technologies in actual village situations that we cannot answer this question completely. However, some preliminary calculations suggest that at least five technologies now "on the shelf" are, or soon will be, cost effective when compared with either diesel electric generation or the existing electric grid in the case of Tanzanian vil-

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