Solar Biomass Energy: An Overview of U.S. Potential

Use of wood fuel for small-scale space-heating applications is an important near-term opportunity.

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Summary. The U.S. annual biomass production for food, lumber, paper, and fiber, if used exclusively for energy, would provide 25 percent of current energy requirements. The collection of unharvested wood residues and cull trees for direct use as fuel for small nearby space-heating applications—especially for peak winter conditions—is an important near-term solar energy opportunity. Improved management of hundreds of millions of acres of productive forest land is an important opportunity for the long term. Harvest of cropland residues for energy values, new biomass production using intensive short-rotation silviculture, resubstitution of natural products for petroleum-based synthetics, and forest management for large-scale production of electricity and synthetic fuels are judged to be less appropriate directions for the U.S. energy system to take.

Solar energy is an alternative energy source to replace diminishing supplies of oil and natural gas. The U.S. government supports a growing list of research, development, and demonstration activities aimed at an early introduction of promising solar energy processes and technologies. Emphasis is given primarily to two general uses: direct space heating and electricity generation. Suitable technologies are available, although not perfected, to make use of sunlight in these two ways. However, it is generally agreed that, for most locations in the United States, conventional fuels will continue to be less costly than these applications of solar energy for several years to come.

Solar energy is abundant, well distributed, and inexhaustible. To its detriment, it is diffuse; it varies in intensity geographically and seasonally; and it is intermittent. The diffuseness of sunlight imposes energetic and economic burdens on its collection and use—particularly on its immediate use. For example, not only must large areas be covered by energy-collecting devices, but also the energy required to produce the collecting equipment, to transport it from point of manufacture to the solar field, and then to transmit the collected energy back to the point of use can be a significant fraction of the energy gained.

The earth's inconstancy in its attitude toward the sun gives rise both to our need for energy and to the cost of using solar energy. The sun falls unequally on the earth in time and location; thus, about 30 percent of our fossil fuel is used to keep us warm when the sun is inadequate and to cool us when it is too strong. For solar energy, we incur high costs because we must first purchase a great surplus in equipment to capture extra energy when the sun is shining and then we must buy the equipment to store the surplus energy that was collected in order to have it when we need it.

The difficulties of collecting, storing, and distributing solar energy have been generally recognized and provide much of the impetus to an increasing interest in the possibility of biomass production. The collection of solar energy as biomass provides solutions to the problems of high collector cost, of capturing some of the sun's energy in any location whenever it is available, and of storing that energy for use when fuel is needed. In addition, some of the energy costs for energy transmission are reduced by the biomass opportunity because the biomass need be harvested only periodically—at intervals of one or more years.

Two other attributes of biomass energy should be presented although the associated benefits are difficult to assess quantitatively. One is that biomass production, as now practiced in agriculture and silviculture, represents an accepted and desirable pattern of conservative land use. Both agriculture and silviculture are important social endeavors with histories of successful application of research and development results. Thus, biomass energy production can build on and contribute to these important sectors of the economy. The second attribute is that the rural economies of many developing nations, which might otherwise be particularly vulnerable to rising costs for imported fossil fuels, would be adaptable to biomass opportunities for energy production.

In this article, I describe, in energy terms, the present U.S. terrestrial biomass enterprise (that is, agriculture and silviculture) (*1*). Each major category of land use is examined for its present utilization and potential contribution to the production of biomass fuel. The role of specialty crops and the energy relationships of intensive as compared to extensive use of land for biomass production are discussed. To gain perspective on the availability of large areas of land for production of energy, markets for biomass production are reviewed, including a consideration of the importance of exports and livestock production to U.S. agriculture. Finally, some general reflections are provided on environmental issues and the potential for increasing photosynthetic efficiency. From this general overview, opportunities for improving the contribution that biomass can make to U.S. energy requirements are assessed.

Energy Supply and Consumption in the United States

In 1975 the United States used about 71 quads (1 Q = 10^{15} Btu) of energy for all purposes (*2*). Except for the 5 Q contribution from hydroelectric and nuclear, the rest came from the fossil fuels: 13 Q from coal, 20 Q from natural gas, and 33 Q from oil of which about one-third was imported. These data include the oil and gas used as feedstock for the petrochemical industry; thus 1 to 2 Q of the 71 Q total appear in the form of consumer goods (such as plastics, synthetic fibers, and fabrics) rather than as energy.

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Traditionally, energy accounting has not included the contribution from biomass. Presumably, the purposes of biomass production are, like petroleum feedstock, primarily for consumer goods (food, paper, construction materials). Even so, about 1 Q of energy is produced annually from burning biomass (*3*). As is shown below, energy values for biomass that appears annually as consumer goods are much larger.

Agricultural and Silvicultural Biomass Production

About 20 percent of the 1900 million acres (1 acre = 0.4 hectare) in the 48 contiguous states is cropland. In 1974, about 330 million acres were harvested (*4*). Major crop acreages, yields, and energy values are summarized in Table 1. All specialty crops (such as fruits, vegetables, nuts, tobacco, flowers, and seeds), although quite important to agricultural economics, represent only a small fraction of our cropland dedication. According to the data and energy values given in Table 1, cropland agriculture produces energy totaling about 12 Q annually, of which about 40 percent is represented by residues left on the land. Also, the gross yield (including residues) averages about 2½ tons per acre and contains 35 million British thermal units (MBtu) per acre for most of the nation's best lands under good management.

Table 1. Major agricultural crops: land use and production in 1974.

Commodity	Acres (million)	Million dry tons		Energy production*	
		Crop†	Residue‡	Per acre (MBtu)	Total (Q)
Grains	158	215	303	45(25)§	7.1(3.9)
Wheat	66	48	116	34	2.2
Corn	65	142‖	142	61	3.9
Oats	13	9	24	34	0.5
Sorghum	14	16	21	37	0.5
Green crops	74	153		29	2.2
Hay	61	117		27	1.7
Silage and sugarcane	13	36		39	0.5
Oilseed	68	41	34	18(6)	1.2(0.4)
Soybean	53	34	29	19	1.0
Cotton	13	5	4¶	11	0.2
Peanut	2	2	<1¶	21	<0.1
Fruits and vegetables	9	13		20	0.2
Total	309	422	337	35	10.7

*Based on energy values in MBtu per dry ton given in (*12*, p. 263): grain, 15; oilseed, 18; forage crops, 14; fruits and vegetables, 2 (wet basis); residues, 13. †Crop moisture percentages taken from (*42*): wheat, 10.6; corn, 12.9; oats, 7.7; sorghum, 12.8; hay, 8.0; silage, 75.0; soybean, 8.0; cotton, 8.0; peanut, 6.0; fruits and vegetables, 85.0. ‡Taken from (*3*, p. 6), and adjusted for differences in harvested acreages. §Residue values in parentheses. ‖Includes corncobs. ¶Estimated to be half as much per acre as soybeans.

The Forest Service considers 500 million acres of forest land to be commercial—that is, capable of producing stemwood in excess of 20 cubic feet per acre per year (1 foot = 0.3 meter) (*5*). As shown in Tables 2 and 3, the energy value of stemwood growth equals 11 MBtu/acre-year and totals 5.6 Q. Since stemwood represents 55 to 70 percent of the total tree (*6*), the total biomass growth in commercial forests is somewhat in excess of 9 Q annually, and the average energy yield is about 18 MBtu per acre. However, practical limits may exclude leaves, roots, and small branches from these values, thus reducing them to 6.8 Q and 13.5 MBtu per acre-year, respectively.

In contrast to cropland, most of the forest land is not actively managed for production, except for the 13 percent that is industrially owned. The National Research Council estimates that the forest yields could be doubled if the forests were subjected to improved management (*7*). If so, acre for acre, the forest land energy production potential could become comparable to that for cropland.

The difference, of course, between cropland and forest land production is that the forest yield can be accumulated for many years. For example, the average inventory on forest land is about 715 MBtu per acre (that is, 430/~ 0.6) or about 20 times the annual cropland yield. (The yield of each acre actually harvested would, of course, be expected to be considerably higher than the average inventory for all forest land.) The forest inventory represents more than 38 years of tree growth on the average, and an energy inventory that is three times our annual usage of energy in all forms.

Table 2. Commercial forest land statistics for 1974 by region. Data for the tree include trunk only to the point of major branching or to a minimum bark diameter of 4 inches (*5*, pp. 26 and 246–247).

Area	Production				
	Total			Per acre	
	Cubic feet	Btu*	Softwood (%)	Cubic feet	Btu*
		Stemwood inventory			
Northeast	174.4×10^9	57.6×10^{15}	25	980	323×10^6
Southeast	184.5×10^9	55.4×10^{15}	49	959	287×10^6
West	355.6×10^9	99.4×10^{15}	93	2770	777×10^6
Total	714.5×10^9	212.4×10^{15}	67	1430	430×10^6
		Annual growth			
Northeast	5.5×10^9	1.8×10^{15}	25	31.1	10.3×10^6
Southeast	8.6×10^9	2.6×10^{15}	63	44.6	13.4×10^6
West	4.4×10^9	1.2×10^{15}	88	34.2	9.6×10^6
Total	18.6×10^9	5.6×10^{15}	57	37.1	11.1×10^6

*Hardwood basis, 8000 Btu/lb at 44 pounds per cubic foot; values typical for dry oak, hickory, and maple; softwood basis, 8400 Btu/lb at 32 pounds per cubic foot; values typical for dry fir and pine (*43*).

Table 3. Commercial forest land acreage and ownership for 1974, in 10^6 acres, by region (*5*, p. 11).

Area	Acreage	Land ownership				
		Federal	State and local	Industry	Farm	Private
Northeast	177.9	12.3	19.6	17.6	51.0	77.4
Southeast	192.5	14.3	3.0	35.3	65.1	74.8
West	129.3	80.6	6.4	14.4	15.0	12.8
Total	499.7	107.1	29.0	67.3	131.1	165.1

Other Terrestrial Biomass

In addition to cropland and commerical forest, major land classifications include urban area (60 million acres), noncommercial forest (100 million acres), pasture and range (715 million acres), idle cropland (50 million acres),

Table 4. Potentially collectable net yield from U.S. biomass operations under present management practices (1974).

Activity	Gross energy yield (Q)	Collectible net energy yield* (Q)
Agriculture		
Corn	3.9 (1.9)†	3.0 (1.8)
Grains	3.2 (2.1)	2.9 (2.0)
Green crops	2.2	2.1
Oil seeds	1.2 (0.4)	1.1 (0.4)
Fruits and vegetables	0.2	0.2
Other‡	0.7	0.6
Silviculture	9.3 (3.7)§	6.6 (1.2)‖
Pasture and range	7.0	0.7
Total	27.7 (8.1)	17.2 (5.4)

*Energy inputs valued at 1.5 times the value of biomass energy. †Residue values given in parentheses. ‡Taken as 10 percent of the total for all agriculture excluding corn in order to account for minor crop acreages not included in Table 1. §All residues. ‖Excludes tree leaves, small branches, and roots; includes stump, unmerchantable bole, and large branches.

and other (135 million acres of swamp, sand dune, desert, bare rock, and national and state preserves) (*8*). With the exception of idle cropland and cropland pasture, these land areas (without irrigation) would seem potentially capable of making only a limited contribution to biomass production. The largest land category, pasture and range, produces perhaps as much as 7 MBtu per acre (*9*) for a total of 5 Q annually. If the other areas are no less productive, the energy production might total 7 Q for these marginal lands taken all together.

Energy Requirements

Several investigators have estimated ratios of energy output to input for major crops: corn, 2.5 (*10*) to 3.3 (*11*); wheat, 5.4 (*11*); alfalfa, 16.0 (*12*); forest logging, 37 (*13*). These data do not account for the harvest residues. Since the residue yield is substantial and since most of the energy inputs for crop production are for nonharvest operations, a high ratio of output to input energy for incremental harvest of cropland residues would be expected—perhaps 40 : 1 or more—and would be comparable to tree stemwood production where energy requirements are totally associated with the harvest. When this adjustment is made, the ratios of output to input for whole-plant harvest of grains become 5.2 for corn and 13.0 for wheat. When computed in this way, the inverse proportionality between the energy output to input ratio and the yield is apparent (Fig. 1). This relationship is true, of course, because the solar energy input is not included.

For forest land and cropland, energy inputs come from very high quality sources: gasoline, commercial fertilizer, electricity. Even at its best, biomass fuel is not fully dried, is bulky, and has low heat content per pound relative to fossil fuels. To account for this difference, energy inputs to biomass production should be valued considerably higher—say 50 percent (*14*)—than the biomass energy produced unless, of course, the biomass can be directly substituted for oil or gas on a Btu-for-Btu basis.

For pasture and range land, a different relationship exists: the grazing animal provides the harvest energy, but in so doing the harvest yield is reduced by a factor of 10 or more (*15*). A precise value for the factor is not needed to establish the point that the collectable energy yield from rangeland under present management practices is quite low (less than 1 MBtu/acre-year).

At this point, we can make a rough estimate of the current net biomass energy production for the United States that attempts to account for the energy to produce and collect it. These estimates are shown in Table 4. The major differences between gross energy yields and the computed net yield exist because (i) there is a high energy input associated with corn production; (ii) certain forest residues are judged to be relatively uncollectable; and (iii) rangeland production is collected inefficiently in terms of its use for energy.

Biomass Residues Summarized

Opportunities for energy production from biomass exist at one extreme in the use of collected biomass wastes, and at

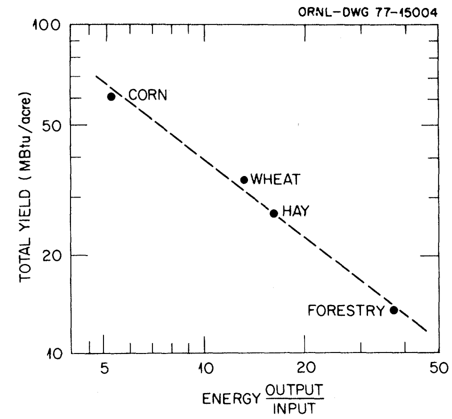

Fig. 1. Inverse proportionality of major crop yields and the ratio of energy output to input.

the other extreme in new biomass production. In between lie possibilities for the use of uncollected biomass residues. At first glance, the priority for the use of biomass for energy production would seem to flow downward from the use of collected wastes that would otherwise have to be disposed of, to the collection and use of residues that are available for the taking, and, finally, to new production.

A summary of biomass residue tonnages and energy contents from major sources is presented in Table 5. Also shown are the estimated residue energy densities per acre for cropland and forest land (*16*). These estimates show that energy density per acre of forest residues is higher, and that wood itself is a much denser form of fuel (for example, 1 cubic foot of wood contains as much energy as 5 to 10 cubic feet of baled field residues). In addition, dead and cull trees from harvested forest land are not included in the figures for logging residues. Dead, rough, and rotten trees, on the average, constitute 9 percent of the forest inven-

Table 5. Major sources of potentially usable biomass residues.

Item	Weight (10^6 dry tons)	Energy* Total (Q)	Energy* Per acre (MBtu)
Collected			
Urban and municipal solid wastes†	160	2.1	
Large poultry and hog operations and cattle feedlots‡	26	0.3	
Large canneries, mills, slaughter houses, and dairies‡	23	0.3	
Wood manufacturing§	15 to 27	0.4	
Total	~230	~3	
Uncollected			
Cereal straw	161‖	2.1	22
Cornstalk	142‖	1.8	28
Logging residues§	50 to 75	1.1	130¶

*Residues evaluated at 13 MBtu per dry ton except for wood residues at 17 MBtu/dry ton. †(*3*), p. 6. ‡(*7*), p. 217 §(*3*), p. 4; (*7*), p. 217. ‖See Table 1. ¶Estimated by the author assuming the large branches, stump, and unmerchantable bole are collected and that the total average aboveground residue is 9.1 dry ton/acre as given in (*6*, p. 75).

Table 6. Major markets for field crop production, 1973 (*4*).

Commodity	Acres harvested (millions)	Market share of net production, (10^6 acres)*		
		Livestock	Export	Other domestic
Corn	62	45 (72)	13 (21)	4 (7)
Wheat	54	7 (12)	32 (60)	15 (28)
Soybean	56	20 (36)	34 (60)	2 (4)
Oats	14	12 (86)	1 (8)	1 (6)
Sorghum	16	12 (75)	4 (25)	
Barley	10	5 (52)	2 (19)	3 (29)
Hay	62	62 (100)		
Silage	10	10 (100)		
Cotton	12†	4 (33)	4 (30)	4 (37)
Total	296‡	177 (60)	90 (30)	39 (10)

*Acreages were calculated based on the fraction of the total weight of the harvest utilized for each market. Values in parentheses are percentages. †About half the weight is lint and linters of which about half is exported. The other half represents oil, cake, and meal; hulls are not included. ‡This represents about 90 percent of the total cropland harvested.

tory (*5*, p. 27). Thus, there is the opportunity to improve the quality of the stand of the remaining growth stock even as dead or deformed standing inventories are collected.

Intensive Tree Farming

The concept of intensive tree farming has recently received much attention (*17*). The concept applies the elements of cropland agriculture (high machinery use, high fertilizer use, short rotation harvesting) to growing trees. It is hard to assign high priority to this technique when there are millions of acres of underutilized forest lands (*18*) that await even rudimentary management. Expected ratios of energy output to input from intensive tree farming are predictably lower than those routinely obtained through traditional forestry operations even if very high yields (*19*) can be achieved as claimed; and, of course, the energy inputs are in the form of oil and gas. While very high yields may be possible, there is a need to distinguish between what is possible and what is practical on a large scale. For example, in agriculture, record yields for small acreages may be four to eight times higher than average yields (*20*).

Finally, evidence to support the view that annual yields obtainable through short rotation tree farming will exceed those obtainable through traditional forestry is not convincing—especially when the comparison is made for comparable levels of management and cultural practice. Indeed, considerable evidence shows that high yields in traditional forestry are obtained after a few years of growth and that these yields can continue for ten or more years (*21*). At present, the choice between coppice forestry, with artificial replacement of nutrients lost in small branches and leaves, and the harvest of stemwood at 10- to 20-year intervals, seems to favor traditional forestry.

Specialty Crops

A massive "Emergency Rubber Project" (ERP) was initiated in February 1942. More than 1,000 scientists and technicians were assigned to guayule production and research. In 3-1/2 years, supported by a work force of 1,000 workers, the ERP planted almost 32,000 acres of guayule at 13 sites in 3 states. It produced one billion guayule seedlings and 3 million pounds of resinous rubber for the war effort.

The preceding excerpt (*22*) is used by its authors as support for the report recommendations calling for government R & D for commercialization of guayule production. The Native Latex Commercialization Act would provide $60 million over the next 5 years to accomplish that purpose (*23*). But 3 million pounds of rubber in 3 ½ years from 32,000 acres of carefully managed irrigated land is less than 0.02 ton per acre per year. By way of comparison, the average oil yield from the peanut crop is currently about 0.5 ton per acre. Thus, whatever other benefits may result from attempts to establish a natural rubber industry, the case for guayule as an energy producer has yet to be made. This is in spite of the views as stated in the introduction to the National Research Council Report (*22*):

Petroleum, our major source of hydrocarbons, is dwindling and is now widely predicted to run out within a few decades. Thus, today, a plant that produces hydrocarbons—as guayule does—is particularly worthy of investigation.

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Agricultural Markets

We gain some appreciation of the possible future availability of large land areas for energy production by considering the current markets for cropland production. In order of acreage, markets for field crops may be divided into three general categories: livestock feed, export, and other domestic uses. These major categories of demand are compared in Table 6 in terms of acreage commitments (*4*). As shown, of major field cropland, 60 percent is dedicated to the production of livestock, 30 percent to production for export, and 10 percent to production for other domestic purposes. The data in Table 6 exclude the contribution that 716 million acres of pasture and rangelands make to livestock support.

Some measure of the overall efficiency of animal production for food is indicated in Tables 7 and 8. These data suggest that, on a dry weight basis, the edible portion resulting from livestock production is about 4 percent of the harvested yield from the dedicated land. Of course, some of the cropland products for animal feed are by-products of other markets (cottonseed and soybean meal), but by and large these are relatively minor activities in the overall livestock enterprise. If we attempt to account for the use of pasture and rangelands, then the efficiency of meat production is further reduced by perhaps a factor of 2 (*24*).

With no intent to judge or influence the actual course of future events, one can note the vulnerability of the U.S. agricultural system to potential changes in its dominant markets. Just as margarine (soybean oil) replaced butter in the 1940's, so might meat substitutes better satisfy future consumer preferences for reasons of both economy and health (*25*). Such a change would take place over decades and, in all probability, would never be complete. Overall implications are illustrated with an extreme example. It can be shown that the basic ingredients to provide 3000 kilocalories per day for 210 million people on a U.S. recommended diet (*26*) could be produced on about 9 percent of the present cropland acreage, that is, 15 million acres each of corn and peanuts, based on current average yields for those crops in contrast to the 240 million acres that are now being used.

The foreign market for grain may not be unlimited. There may be limits in the degree to which importing countries are willing to become dependent on the United States for basic food. There may be financial limits in the ability of developing countries to purchase their food imports or there may be limits in our willingness to subsidize their needs. Finally, there are real questions regarding the efficacy of grain as compared to oil imports for developing countries that have rural economies based on labor-intensive agriculture.

Markets for Industrial Materials from Renewable Sources

Traditional industrial products based on biomass include sawtimber products, primarily for building construction, and pulpwood for the paper industry. Also important, but much smaller markets in terms of volume, include cotton, wool, and cellulose fibers (rayon), and special products and by-products of agriculture and forestry, such as leather, turpentine, and soap.

Beginning in the 1940's, synthetic products, primarily made from petroleum, have rapidly replaced traditional biomass products: first synthetic rubber and detergents, and now a wide variety of synthetic fibers and plastics each formulated to provide the right properties for each specific consumer requirement. More recently, synthetic products are competing favorably with paper and structural products as well (for example, plastic bags and vinyl siding).

Recent demands for industrial biomass materials are given in Table 9. Also shown are the markets for synthetic plastic, rubber, and fiber. The data are given in terms of product tonnage and approximate energy content. These data show that the opportunity for a significant contribution to energy conservation or supply through an attempt to recapture markets lost to the petrochemical industry seems not to exist. This is because the total market opportunity is small, and because little, if any, energy would be saved relative to the use of biomass directly as fuel (*27*). Also, a significant fraction of the energy content of petrochemical feedstocks ends up in the products themselves. Thus, as long as product energy values are ultimately recovered through recycle or as residues for use as fuel, the original form of the feedstock is of secondary importance. Finally, the synthetic products, in general, have a longer useful life than do natural products and, to the extent that our society moves toward recovery of energy values in solid wastes, the biodegradability of natural products is not an important advantage.

Conversely, forestry activities could make a contribution to fuel supply through additional forest production, additional forest residue use, and through recovery of forestry products (wood and paper) at the end of product life. Certainly, direct use of wood and wood products as fuel in place of petroleum and gas seems intuitively much easier to accomplish than does restructuring the petrochemical industry and changing consumer product preferences.

Table 7. Major livestock production in the United States in 1974 (10^6 ton).

Commodity	Weight		
	Live*	Dressed*	Edible†
Beef	19.6	11.0	3.4
Hogs	10.7	6.2	2.4
Sheep	0.4	0.2	0.1
Chicken	6.2	4.3	0.9
Turkey	1.2	1.0	0.3
Milk	57.7		4.4*
Eggs	3.7		0.8*
Total	100.3		12.3

*See (*4*). †Estimated protein, fat, and carbohydrate content of dressed meat weights (dry weights) based on data in (*44*).

Table 8. Major livestock feed crops.*

Commodity	Consumption† (10^6 dry tons)
Corn	102‡
Wheat	4.6
Soybean	13.8
Oats	9.8
Sorghum	17.1
Barley	5.2
Cottonseed	2
Silage	30.6
Hay	124
Total	309.1

*The time periods associated with data in (*4*) for feed disappearance and livestock production are not exactly comparable. †Basic data for year beginning in mid- or late-1973 from (*4*); commodity moisture contents taken from (*42*). ‡Grain only, although corncobs are also used for cattle feed.

Table 9. Demands for industrial biomass materials and for synthetic plastic, rubber, and fiber in 1972 (*7*, pp. 65, 202, and 228).

Commodity	Tonnage (10^6)	Energy (Q)
Round wood requirement		
Structural materials	123	2.1
Pulp, paper, fiber	102*	1.7
Cotton and wool fiber†	3	0.2‡
Biomass extractives		
Turpentine, rosin, tall oil§	1	
Vegetable oils‖	1	
Animal fat‖	1	
Animal hides	2	
Synthetics		0.6¶
Plastics	12.5	
Fibers	3.1	
Rubber	2.8	

*Cellulose fibers account for less than 1 million tons. †Includes exports. ‡Total for cotton and wool fiber, biomass extractives, and animal hides. §Major uses include pine oils, rubber additives, paper size, adhesives, insecticides. ‖Major uses include fatty acids, soap, and drying oils. ¶Total for all synthetics.

The production of nitrogenous fertilizers is not included in Table 9. Total consumption in 1973 was 10 million tons of contained nitrogen (*4*, p. 469). On the basis of 19,000 cubic feet of natural gas used per ton of ammonia produced (*28*), the nitrogenous fertilizer industry consumed 0.2 to 0.3 Q of natural gas in 1973, which represents about 1 to 2 percent of natural gas use for all purposes. Again, the total market is small.

Ammonia could be produced from the direct processing of biomass or, alternatively, the demand for ammonia could be reduced through the development of agronomic crops with an enhanced capability to fix their own nitrogen. Favorable economics for ammonia production require a large-scale operation. For example, an ammonia plant yielding 300 tons per day would require the annual yield from 250,000 acres of forest or else five times that area if woody forest residues were to be the sole raw material source. Thus, biomass production or residues are unlikely to compete with concentrated fossil fuels for the ammonia industry.

The prospects for direct plant fixation of nitrogen would seem promising, but the issue is not simple even if the uncertainties concerning the outcome of the needed research program are disregarded. For example, research on vegetative peas gave the result that the plants consume four weight units of carbohydrate to fix one weight unit of nitrogen (*29*). Synthetic fixation of nitrogen requires only about half as much energy per unit of fixed nitrogen production, suggesting that, from an energy systems standpoint alone, we may be better off using natural gas for ammonia production and biomass for fuel rather than the reverse. At the very best, the results do indicate that changing our present methods may produce only minor gains.

The Market for Biomass Fuel

It is fair to say that a significant demand for biomass fuel is lacking because homes, schools, churches, stores, apartment buildings, and small business establishments are not at present equipped to use such fuels directly. Some biomass industries (sugar, paper, wood products) do use feedstock wastes for some of their fuel requirements.

There are markets for natural gas and petroleum that are satisfied by fuel imports. Because of this, indirect production of gas and oil from biomass, rather than development of direct fuel markets for biomass, has received the major emphasis.

It is not the purpose of this article to review alternative processes for converting biomass residues to electricity or convenient forms of fossil fuels. Favorable economics of electricity generation and chemical processing depend to a degree on large-scale operations. They also depend on favorable conditions for handling raw materials (such as high energy density, pipelining). These attributes are not characteristic of forest and field residues. Biomass residues must be collected in bulky form from large areas at a high cost in labor and transportation; thus, they are unlikely to compete generally with coal or shale oil as feedstock for centralized industrial production of synthetic fuel gas and liquids.

For small-scale operations and under favorable conditions for growth of biomass, production of liquid fuels from biomass may be more competitive. The government of Brazil is embarking on an aggressive program of alcohol production from cassava and sugarcane, as a substitute for imported oil, and at the same time to encourage settlement and development of the Amazon Basin (*30*). Here, the combination of low-cost labor and low-cost land, small rural populations and related energy demands, difficult logistics of supply from the coastal cities, and a long growing season and tropical climate seem ideally suited to the government policy.

The conditions for biomass alcohol production in the United States are almost completely opposite those for Brazil (*31*). In addition, in the United States, the outcome of a net energy analysis is less certain and more complex because of the high energy requirements for corn production. (Corn is the only crop presently grown in the United States with a scale of production large enough to make a significant impact from biomass alcohol.) For example, at the margin, in U.S. corn culture 1 pound of additional nitrogen might be expected to produce an additional 4 pounds of grain yield (*32*). Since it would take the energy from about 3 pounds of grain to produce 1 pound of nitrogen fertilizer, the potential net gain in energy seems marginal even without considering other energy uses for the complete system. Thus, in the absence of the availability of large quantities of surplus agricultural land that would allow corn production for biomass alcohol with lower inputs of fossil energy, it is not obvious whether the U.S. energy balance would benefit or lose from biomass alcohol (*33*).

> A point about solar energy that government planners seem to have trouble grasping is that it is fundamentally different from other energy sources. Solar energy is democratic. It falls on everyone and can be put to use by individuals and small groups of people. The public enthusiasm for solar is perhaps as much a reflection of this unusual accessibility as it is a vote for the environmental kindliness and inherent renewability of energy from the sun.

This view from Hammond and Metz (*34*) appears to be only slightly less valid for solar biomass energy. If so, perhaps a relatively neglected area for consideration is the creation of a demand that substitutes wood residues directly for oil and gas use. This demand could be created among the users of small amounts of energy (for example, schools, stores, residences) that presently depend on oil and gas for space heating. In this sense, solar biomass is a natural complement for direct solar heating. Wood fuel could also supplement the use of electricity for space heating during peak demand periods. Electric resistance heaters are frequently used in electrically heated homes for peak heating requirements on the coldest days, even for homes equipped with more efficient heat pumps. These supplies of electricity are, in turn, typically generated in power stations fueled with gas and oil.

Machinery for whole-tree chip harvesting and equipment for efficient combustion of wood for steam generation and space heating are currently available. Wood fuel is available in many locations at costs competitive with other fuels or nearly so (*35*). Major barriers to increased utilization of wood as a fuel include: acceptance of wood as a practical fuel on a small scale; installation of efficient wood-burning equipment; adequate incentives for harvesting cull trees, deadfall, and sawtimber residues; and incentives to replace trees removed with improved growing stock.

Environmental Considerations

The full range of environmental issues related to greatly expanded production and use of energy from biomass have yet to be addressed. We already have measures of potential problems in the form of the current effects of agriculture—these include stream pollution arising from soil and fertilizer runoff and loss of productive lands through overgrazing, deforestation, and irrigation salting.

Environmental considerations compel us to place high priority on energy production from collected biomass residues. Otherwise, we must accept the high cost and further environmental degradation resulting from disposal.

With regard to uncollected biomass residues from forestry and farming, we note that the annual taking of field crop residues represents the taking of both nutrients and humus from the soil which, at some point, must be replaced if the soil quality is to be maintained. These effects will also occur with the taking of forest residues, but to a lesser extent. For example, partial forest harvests at multiyear intervals ensure that annual residues (leaves, deadfall) are available for maintaining forest floor conditions, and, even at harvest, about one-fourth of the plant—small branches and roots—would be left behind. Woody forest residues contain perhaps only 30 percent as much nitrogen as do wheat and corn residues (*36*), which make up three-fourths of the total field residues.

The carbon dioxide content of the atmosphere is increasing, primarily due to the growing use of fossil fuels since the industrial revolution (*37*). The concentration has increased 5 percent in the last two decades alone. The long-term effects of this trend are uncertain both in time and magnitude but are potentially serious. A new dimension to the problem was introduced by Bolin (*38*) who estimates that the accumulated input of carbon to the atmosphere due to deforestation and expansion of agriculture (that is, the loss of carbon from the soil) is 50 ± 25 percent of the amount transferred to the atmosphere from fossil fuel combustion.

Biomass wastes are soon returned to the atmosphere by natural processes in the form of heat, water, and carbon dioxide. Thus, to the extent that their use as fuel can supplant the combustion of fossil fuel, release of carbon dioxide and sulfur dioxide could be reduced both because the total amount of fuel burned would be lower and because the sulfur content of plant residues is lower than it is for fossil fuels.

The implications for biomass energy seem clear: priority should be given to ways through which we may derive energy from biomass while maintaining or augmenting carbon inventory in land biota and soil. If history is a guide, reforestation and improved forest management seem potentially able to meet these criteria.

Photosynthesis

There is no evidence that the graph in Fig. 1 (showing yield proportionality with energy input) represents immutable biological law. Still, the implications seem clear: the biggest gains in biomass production for the least expenditure of high value fossil fuels are to be made not at the margin represented by corn but, rather, at the other extreme represented by forestry. Indeed, it is discouraging to plot extremely high yields (such as 30 dry tons per acre) on the graph because we would then predict a net loss in energy yield or a mining of the soil resource that could not long be sustained in nature (*39*).

Bassham has estimated the theoretical maximum daily photosynthetic energy conversion of incident sunlight at 6.6 percent and shown that maximum rates during the growing season may reach half this calculated value for C_4 plants (*40*). For the United States, this 50 percent of theoretical value corresponds to 50 tons/acre-year if the conversion rate could be maintained throughout the year. In fact, such yields have been achieved on limited acreages of specialty crops, such as sugarcane, that have a long growing season and nearly optimum growing conditions of sunlight, temperature, rainfall, and rich soil. For much of the United States, however, such conditions do not exist. For example, the maximum measured daily photosynthetic energy conversion rate for corn exceeds that for sugarcane by almost 40 percent but on an annual basis the photosynthetic productivity of corn is only about 10 percent that of sugarcane. The point is not that further improvements in photosynthetic productivity are not possible, but that reasonably high photosynthetic conversion efficiencies are already being achieved (*41*), and that other factors, such as growing season, may be of primary importance in achieving high annual yields for energy crops. Here again, tree crops, with maximum growing season and minimum loss through respiration during the dormant season, are suggested.

Conclusions

Based on this analysis, the total of each year's biomass production in the United States for all purposes—not only fiber and wood but also food—might, if used for energy, suffice for 25 percent of the nation's annual energy needs. We conclude, therefore, that biomass energy must be regarded as a relatively minor contributor to the U.S. energy system at least for the next few decades.

Nearly 90 percent of cropland is used for production of livestock feed and grains for export. Thus, a shift in food preference away from animal protein or a reduction in the demand for grain exports could conceivably release high quality agricultural land for energy crops. Such changes, should they occur, would take place in relatively small increments over many years.

At present, several hundred million acres of public and private forest land is not managed for tree growth—even when multiple use goals are considered. Much of this land is in the eastern half of the United States, in reasonable proximity to rural, town, and suburban areas of energy demand. Forestry has unique characteristics that make it particularly suitable for biomass energy production: the energy harvest per acre can be many times that for annual crops; wood is a dense storable form of biomass fuel; trees grow productively for many years and thus provide live storage from year to year without loss of yield; nutrient losses in forestry are relatively small; wood fuel burns relatively cleanly. These factors suggest that the best present opportunity for new biomass production could be realized through programs that provide incentives for better forest management. In this way forest quality and growth rate could be increased even as low quality forest stands and forest residues are harvested for fuel.

Experience in agriculture shows that a prerequisite for high crop yield is high energy input to production. In agriculture, the increase in yield is in the form of a high value product such as grain; thus, these high energy inputs of fossil fuels seem appropriate. However, it is less apparent that large inputs of high value fuels (gas, gasoline, electricity) can be justified in the production of lower value biomass energy either in the form of agricultural crops or by intensive short-rotation tree-farming concepts. This seems especially true in the light of opportunities to use biomass residues and to increase forest growth rates marginally through less energy-intensive means.

The contribution to energy supply that could be achieved through replacing synthetic rubber, plastics, and fiber with products derived from biomass resources is relatively small in total. In addition, a comparable or even greater energy contribution could be made by using the same biomass directly as a fuel substitute for natural gas and fuel oil. This could be accomplished without the need to reorient consumer preferences away from the many specialized petrochemical products or the need to replace petrochemical industries themselves.

The lack of installed, small-scale equipment for using wood fuel instead of oil and gas is judged to be the primary barrier to expanding the demand for wood. Barriers to development of this market in an acceptable form are: incentives to manage private forest acreages for increased wood production; incentives to harvest forest residues and cull timber; a wood fuel supply industry; and availability and acceptability of products for efficient wood-burning suitable for small-scale users that are now dependent on gas and oil fuels.

References and Notes

1. Aquatic production of biomass is not considered in this paper although its range of technical and biological possibility seems at least as comprehensive as that for terrestrial biomass. Concepts under consideration include (i) use of aquatic plants to feed on nutrient-rich waste waters, thus converting the wastes to more useful products; (ii) harvest of plants growing on unused areas, such as cattails from marshes; and (iii) new production of kelp on ocean farms (suggested by H. A. Wilcox of the Naval Ocean Systems Center in San Diego). In general, aquatic biomass production would be subject to the same overall constraints as land-based activities: photosynthesis, area available, climate, and energy costs for plant culture, nutrient source, transportation, and processing.
2. J. A. Lane, *Consensus Forecast of the U.S. Energy Supply and Demand to the Year 2000* (Report ORNL/TM-5369, Oak Ridge National Laboratory, Oak Ridge, Tenn., May 1977), p. 14.
3. E. L. Ellwood *et al.*, *The Potential of Lignocellulosic Materials for the Production of Chemicals, Fuels, and Energy* (National Research Council, Washington, D.C., 1976), p. 11; available from the National Technical Information Service, Springfield, Va.
4. U.S. Department Agriculture, *Agricultural Statistics 1975* (U.S. Government Printing Office, Washington, D.C., 1975).
5. *U.S. For. Serv. For. Resour. Rep.* (1974), p. 9.
6. K. Howlett and A. Gamache, *Forest and Mill Residues as Potential Sources of Biomass* (Report 7347, Mitre Corporation/Metrek Division, McLean, Va., May 1977), vol. 6, p. 49.
7. National Research Council, *Renewable Resources for Industrial Materials* (National Academy of Sciences, Washington, D.C., 1976), p. 7.
8. U.S. Department of Agriculture Economic Research Service, *Air, Land and Water Resources: Current and Prospective Supplies and Uses* (Bulletin 1290, U.S. Government Printing Office, Washington, D.C., 1974).
9. A. Poole, "Food and fiber project notes" (unpublished paper) (Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tenn., July 1977), exhibit 9.
10. D. Pimentel, in *Energy, Agriculture and Waste Management*, W. J. Jewell, Ed. (Ann Arbor Science, Ann Arbor, Mich., 1975), p. 12.
11. L. D. Hill and S. Erickson, in *ibid.*, p. 118.
12. C. G. E. Downing, in *ibid.*, p. 265.
13. K. C. Hoffman, F. Drysdale, P. R. Eberts, W. McKean, G. Schreuder, G. C. Taylor, N. Bhagat, *Reference Materials System: A Source for Renewable Materials Assessment* (National Research Council-National Academy of Sciences, Washington, D.C., 1976), p. 13; available from the National Technical Information Service, Springfield, Va.
14. By analogy, about one-third of the energy content of coal is used in converting it to higher value synthetic liquid and gas fuels.
15. The assumption is that wastes from grazing animals cannot be recovered.
16. There is, of course, great variation in the per acre quantities of logging residues. For example, J. B. Grantham [in *Status of Timber Utilization on the Pacific Coast* (U.S. Department of Agriculture Forest Service General Technical Report PNW-29, 1974), p. 7] estimates that just the weight of logging residues over 4 inches (1 inch = 2.54 centimeters) in diameter and 4 feet long exceed 57 tons per acre (~ 1000 MBtu) for national forest harvests of Douglas fir.
17. J. A. Alich and R. E. Inman in *Energy, Agriculture and Waste Management*, W. J. Jewell, Ed. (Ann Arbor Science, Ann Arbor, Mich., 1975).

18. In this context the term "underutilized" refers to the practice of minimum management of privately owned forest for many millions of acres. (This is not to imply that minimum management is not rational given current economic conditions.) Some significant fraction of this area is never harvested, and mature trees, both merchantable and cull, topple and decay. For a larger fraction of the acreage, merchantable stemwood is periodically harvested but not replanted, the woody residues and dead stemwood are not removed, and growing cull trees are left to expand their area of coverage.
19. The basis for analysis used in the reference is 30 dry tons per acre-year.
20. S. H. Wittwer, *Science* **188**, 575 (1975).
21. Data from several studies are reported in (*6*).
22. National Research Council, *Guayule: An Alternative Source of Natural Rubber* (National Academy of Sciences, Washington, D.C., March 1977), p. 19; available from National Technical Information Service, Springfield, Va.
23. *Government R&D Report* (U.S. Government Printing Office, Washington, D.C., May 1977), vol. 7, No. 9, pp. 11-12.
24. However, these lands, especially without irrigation, are, in general, only marginally suited for other uses; thus, their harvest by livestock may represent a best use opportunity.
25. C. T. Nisbet, *Technol. Rev.* **79** (No. 7), 5 (1977).
26. The analysis—53 percent carbohydrate, 12 percent protein, 35 percent fat—including consideration of the adequacy of essential amino acids is given by W. C. Yee [*Middle East Study: Nutrition Economics in Desalination Agriculture* (Report ORNL-4489, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1970)].
27. The results of several detailed analyses of the energy requirements to produce competing consumer products using either petroleum or biomass feedstocks are contained in (*7*), pp. 113, 153, and 202. No clear pattern of energy savings emerges. In many cases the energy differences are unimportant relative to product properties that are influential in determining consumer choice.
28. The Conference Board, *Energy Consumption in Manufacturing* (Ballinger, Cambridge, Mass., 1974), p. 266.
29. R. W. F. Hardy and U. D. Harelka, in *Biological Solar Energy Conversion*, A. Mitsui, S. Miyachi, A. San Pietro, S. Tamura, Eds. (Academic Press, New York, 1977), p. 305. Biomass energy is stored in the plant primarily as carbohydrate: cellulose, starch, and simple sugars. A weight ratio of carbohydrate used to nitrogen fixed of four to one corresponds to an energy ratio of about six biomass energy units used as carbohydrate for each biomass energy unit fixed as nitrogen.
30. A. L. Hammond, *Science* **195**, 564 (1977).
31. R. Dubos observes that there is a tendency for developing countries to emulate U.S. high technology regardless of its suitability to their circumstances, and that, if we want to help and encourage these developing countries to adopt and implement other energy policies that are more suitable to their particular economy, we should show them, by example, that these opportunities and related technologies are respectable candidates in the United States as well (René Dubos Environmental Forum, Seven Springs Center, Mt. Kisko, N.Y., 9 to 11 September 1977).
32. L. H. Hill and S. Erickson, in *Energy, Agriculture and Waste Management*, W. J. Jewell, Ed. (Ann Arbor Science, Ann Arbor, Mich., 1975), p. 109. My interpretation of the graph in figure 2.
33. Another approach to U.S. policy governing surplus corn production would consider reduced use of commercial fertilizers in place of restrictions on harvested acreage in exchange for crop price supports.
34. A. L. Hammond and W. D. Metz, *Science* **197**, 241 (1977).
35. P. A. Gnadt and C. D. Murphy, *The Use of Wood as an Alternate Fuel for the ORNL Steam Plant*, unpublished paper, Oak Ridge National Laboratory Continuing Education Program, Course S-600, spring 1977, Oak Ridge, Tenn.
36. W. L. Roller, H. M. Keener, R. D. Kline, H. J. Mederski, R. B. Curry, *Grown Organic Matter as a Fuel Raw Material Resource* (National Aeronautics and Space Administration Contractor Report, NASA CR-2608, October 1975), p. 8; available from the National Technical Information Service, Springfield, Va.
37. C. F. Baes, Jr., H. E. Goeller, J. S. Olson, R. M. Rotty, *The Global Carbon Dioxide Problem* (Report ORNL-5194, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1976).
38. B. Bolin, *Science* **196**, 613 (1977).
39. Discussion at the René Dubos Environmental Forum [see (*31*)] suggests that high sugarcane yields in Florida are due to a one-time opportunity to mine rich muck soils.
40. J. A. Bassham, in *Biological Solar Energy Conversion*, A. Mitsui, S. Miyachi, A. San Pietro, S. Tamura, Eds. (Academic Press, New York, 1977), p. 154. The term C_4 applies to certain plants such as corn and sugarcane that have a special added metabolic pathway. Compared to other plants, the energy efficiency of C_4 plants is higher because they avoid wasteful photorespiration under conditions of high light intensity.
41. Roller *et al.* (*36*, p. 52) conclude, "There are no plant species that will produce biomass more abundantly or more efficiently in the U.S. than our common agricultural crops now grown and/or our forest species."
42. J. H. Martin and W. H. Leonard, *Principles of Field Crop Production* (Macmillan, London, 1967), pp. 1111-1119.
43. O. D. Lorenzi, Ed., *Combustion Engineering* (Riverside Press, Cambridge, Mass., ed. 1, 1952), pp. 25-27; C. D. Hodgman, Ed., *Handbook of Physics and Chemistry* (Chemical Rubber Company, Cleveland, Ohio, ed. 27, 1943), pp. 1238-1240.
44. N. A. Lange, Ed., *Handbook of Chemistry* (Handbook Publishers, Sandusky, Ohio, ed. 8, 1952), pp. 758-768.

NEWS AND COMMENT

The Criminal Insanity Defense Is Placed on Trial in New York

Ever since Daniel M'Naghten, a Scot, was acquitted for erroneously shooting the secretary of his intended victim, the British prime minister, on the grounds that his crime had resulted from a mental defect, courts have in varying degrees considered insanity to be a defense in a criminal trial. M'Naghten's acquittal, which occurred in England in 1843, gave rise to two things: a standard of legal insanity that became widely accepted by courts in the United States, and an immediate public outcry that eventually followed the standard across the Atlantic.

In recent years, opposition to the insanity defense has intensified among the public, presumably because of a perception of it as a means for a criminal to avoid punishment. For example, the initial finding by New York psychiatrists that David Berkowitz, the accused "Son of Sam" killer, was unfit to stand trial on the grounds of mental incompetence prompted unusually hot debate until a New York court partially defused it by accepting the contrary testimony of psychiatrists appointed to give a second opinion. Other recent cases, including that of Patty Hearst, whose lawyers unsuccessfully maintained that she had been brainwashed into helping rob a San Francisco bank, and of Peter Reilly, the Connecticut teenager who successfully claimed he had been brainwashed into confessing to the murder of his mother, have prompted similar debate about the definition of criminal insanity.

This interest has not been lost on lawyers and psychiatrists, who have done a lot of soul-searching recently about their abilities to either predict insanity or to establish it in court. The interest also has not been lost on politicians. Former President Richard Nixon called for an elimination of the insanity defense in the federal court system in 1973. Little was done about his proposal, according to most observers, because it came across as a purely conservative political issue. But the recent notorious uses of the defense have moved the debate out of a purely conservative arena. Last fall, Governor Hugh Carey, a New York Democrat, directed his state Department of Mental Hygiene (DOMH) to prepare a report on how the insanity defense had been used in New York and on the subsequent treatment received by those who used it. "In recent years, there has been widespread concern that the legal defense of insanity in criminal proceedings does not protect the public," Carey said in a message to the state legislature. "Specifically, I have directed the Department to consider the need for limits on a legal defense of insanity."

On 17 February, the DOMH report was released. It is bound to add more controversy to the long-standing debate. Already, it has reverberated throughout the psychiatric and legal communities far outside of New York State, primarily because of its conclusion that the legal defense of insanity should be abolished. Of even greater significance, however, is the 157-page study that accompanied the conclusion. Prepared by a lawyer, a sociologist, and two psychiatrists on the DOMH staff, the study presents a de-