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0273-2289/90/2425—0695$05.00

Large-Scale Fuel Ethanol from Lignocellulose

Potential, Economics, and Research Priorities

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ABSTRACT

Ethanol produced from lignocellulose is considered as a large-scale transportation fuel in the United States. Five key issues are identified and considered in relation to the status of current and foreseeable technology. These are: conversion and production energy balances, suitability of ethanol as a transportation fuel, air quality impacts, raw material supply, and cost. Energy balances and fuel characteristics appear to be consistent with large-scale transportation fuel use of ethanol produced from lignocellulose. Local and global air-quality benefits are expected to accompany use of lignocellulose ethanol. Raw material availability is examined for wastes and for trees and grasses grown as energy crops. Ethanol production levels appear unlikely to be limited by raw material availability as long as economic and other factors are sufficiently favorable to justify allocation of land for this use. Projected ethanol production costs based on current directions of research would allow neat ethanol to become competitive with gasoline by the year 2000 according to current oil price predictions. Biological process steps have the largest contribution to overall costs, are among the least developed aspects of the technology, and appear to have the greatest potential for improvement. Research priorities are discussed.

Index Entries: Fuel ethanol; lignocellulose; economics; biomass.

INTRODUCTION

Practical production of ethanol from lignocellulosic materials has been a goal of researchers since the mid-1970s, and has been a particular focus

Table 1
End Uses for Ethanol

Use	Value	Reference
Chemical feedstock	>Fuel value	9
Blending fuel		
Direct	1.7–2.5 × Crude price (~1.0–1.5 × gasoline)[a]	10
Indirect (ETBE)		8
Neat fuel	0.8 × Gasoline	11,12

[a] With crude oil at 14.71 1988\$/barrel, the wholesale value of ethanol as an octane enhancer is 59.5–87.5 cents/gal according to the OTA (*10*) formula. This may be compared to the 1988 average wholesale price of 57.7 cents/gal for gasoline (oil and gas prices from [*13*]).

at the Biotechnology for Fuels and Chemicals Symposia. Lignocellulosic materials are so called because they contain cellulose, a carbohydrate composed of β-linked glucose subunits; hemicellulose, a carbohydrate composed of xylose and other sugars; and lignin, a heterogeneous aromatic polymer (*1*).

Lignocellulosic materials are a class of raw material distinct from corn, which are characterized by a carbohydrate fraction consisting of cellulose rather than starch. Examples of lignocellulosic materials are trees, grass, and waste paper and cardboard. Both corn and lignocellulose are plant material of recent photosynthetic origin, and can be referred to as biomass. Conversion of corn and lesser amounts of other grains to ethanol is at present the basis for a substantial industry in the US (*2,3*). Ethanol produced from these sources is used as a gasoline additive that raises octane. Approximately 7% of the total motor gasoline used in the US is blended with ethanol (*4*). The economics of corn-derived ethanol are currently dependent on federal subsidies and the value of processing residues as feeds (*2,3*). Brazil has the largest alcohol-fuel industry in the world, with sugar cane as the raw material (*5*). Lignocellulose is not currently a raw material for commercial ethanol production on a significant scale.

The motivations for considering lignocellulose as a raw material are that it is inexpensive, plentiful, and renewable. Lignocellulose is also recalcitrant to biological conversion relative to soluble 6-carbon sugars, such as those that can be produced from corn or sugar cane. Ethanol is an attractive product of lignocellulose processing, in that it can be produced in near-theoretical yields from many carbohydrates by biological fermentation. Furthermore, ethanol is a versatile compound that can be used as a raw material for the chemical process industry (*6,7*), as an octane-enhancing fuel additive (either as ethanol *per se* or ethyl-tert butyl ether [ETBE] (*8*)), or as a neat fuel. Various uses for ethanol are listed in Table 1, along with estimates of the relative value for utilization as a chemical feedstock, blending fuel, or neat fuel. As addressed in more detail below, both

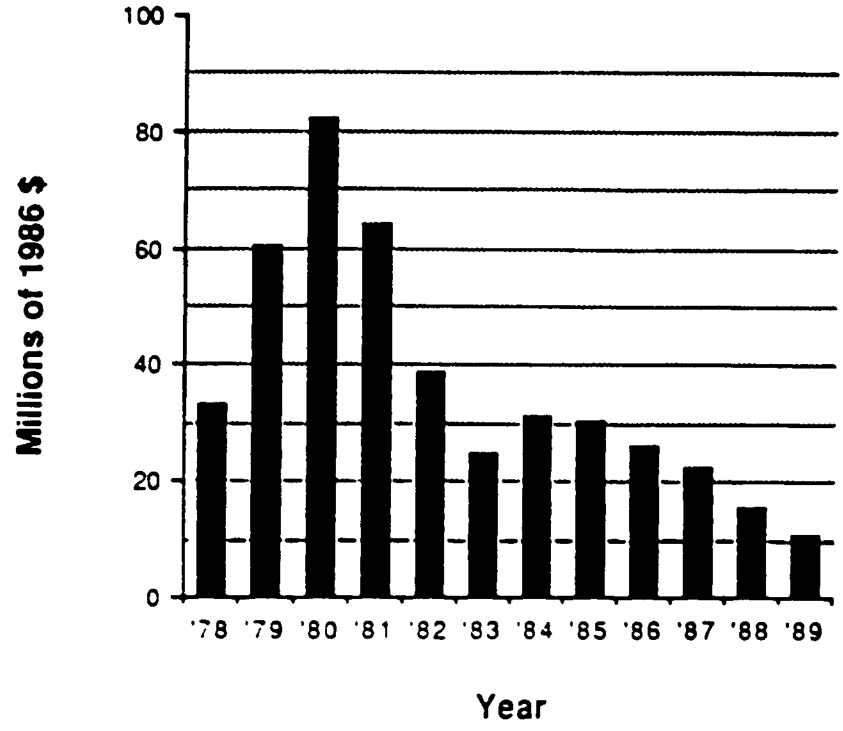

Fig. 1. DOE funding for biomass-related research. Data from (*15*).

strategic and trade-balance considerations are driving forces for developing a large-scale fuel-ethanol industry.

A particular advantage of fuel ethanol produced from biomass is the potential for air pollution abatement. Alcohol fuels, including both ethanol and methanol, have the potential to lower levels of key urban air pollutants. In addition, fuel production from lignocellulose is accompanied by no net contribution to the greenhouse effect (*14*).

Production of ethanol from lignocellulose was an intense focus of research during the early 1980s, motivated by the high cost of oil. Attention and activity relative to lignocellulose ethanol have declined markedly during the 1980s, prompting an exodus of researchers from the field and drastic cuts in remaining research programs. As presented in Fig. 1, the current DOE budget for biomass production and conversion to fuels is more than sixfold smaller than in 1980 (*15*). The decreased interest and support for lignocellulose ethanol is the result of a combination of factors, including a precipitous drop in oil prices, failure to achieve commercial success in the short timeframes that some anticipated, and changing priorities at the federal level.

This paper will consider the large-scale use of ethanol in neat (unblended) form in the United States. As may be seen from Table 1, utilization as a neat fuel will almost certainly achieve market penetration at a later time than other uses, because of the lower value of ethanol in this application. However, neat fuel is clearly the largest-scale use of ethanol, and can therefore be expected to have the greatest impact relative to the economic, strategic, and environmental issues that are motivating factors for ethanol utilization in general. In this sense, large-scale use of neat ethanol is the ultimate goal of research on lignocellulose ethanol. In addition, identifying constraints and opportunities for large-scale fuel use may be helpful in formulating research goals and evaluating progress. Finally, examination of the goal of large-scale fuel-ethanol utilization may be useful in determining the allocation of effort and resources that this fuel path deserves.

BACKGROUND

Important perspectives from which to view the prospect of large-scale use of fuel ethanol include those related to environmental, energy, and economic issues. At present, concern over local and global air pollution are the major factors prompting interest in alternative fuels. The local air-pollution issue centers around high levels of ozone and carbon monoxide in many cities. Over 75 areas in the US exceed national ambient air quality standards for ozone and/or CO (*16*). The EPA (*16*) forecasts that carbon monoxide levels will fall somewhat as a result of turnover of the transportation fleet. However, the number of areas out of compliance with respect to ozone is expected to decline somewhat until 1995, but to increase thereafter.

In 1988, concern over global warming from the "greenhouse effect" increased greatly. According to the statement of the conference on *The Changing Atmosphere* held in Toronto, the ultimate consequences of atmospheric changes "could be second only to a global nuclear war" (*17*). Numerous articles in scientific journals and periodicals have chronicled the debate over whether warming has begun and what extent of warming may be anticipated (*18–23*). In a draft report, "Policy Options for Stabilizing Global Climate," the EPA (*21,23*) states that the scientific community agrees that significant global warming caused by greenhouse emissions will occur throughout the next century. The report concludes further that 57% of greenhouse gas emissions and greenhouse warming is caused by energy use and production, with the next largest contribution at 17%.

Energy production and utilization in the United States is a very large-scale enterprise. As events during the last two decades have demonstrated, changes in energy prices and availability have profound influences on our economy. Oil imports currently compose about a quarter of the foreign trade deficit (*13,24*), with total petroleum expenditures about 2% of the GNP (*13,24*). A consequence of the energy–economy interplay is that alternative fuels will be strongly favored if they can offer lower cost, but will be unlikely to find favor if they do not.

Table 2 presents data for the four major energy sources utilized in the US. It may be seen that petroleum supplies the largest share of total energy

Table 2
Selected Data for US Energy Utilization[a]

Energy source	Annual consumption, quads[b]	Sector with greatest dependence[c]	% imported[b]	Estimated total recoverable reserves: utilization rate[d]
Petroleum	33.9	Transportation, 97%	37	17 y
Coal	18.8	Utilities, 55%	-13	>1000 y
Natural gas	18.6	Res./commercial, 32%	6.6	39 y
Nuclear	5.7	Utilities, 20%	-	-[e]
Other	2.9			
Total	79.9			

[a] All data for 1988.
[b] Data from (*13*).
[c] Data from (*13*); includes indirect contribution as fuels for electric power generation.
[d] Oil and natural gas reserves are from (*25*), for conventional oil and gas. Total recoverable reserves comprise the sum of measured, indicated, inferred, and undiscovered reserves: economically recoverable reserves are a smaller quantity. Coal reserves from (*26*) corrected for consumption up to the present. Utilization rates from (*13*).
[e] US uranium reserves are the largest in the world (*26*).

utilized and has the highest fraction imported, both by significant margins. Furthermore, the domestic supply of conventional petroleum is the most limited of the four major sources. The values given for the ratio of total recoverable reserves: annual utilization rate represent the number of years required to exhaust reserves if we used only our own resources. Imports will lengthen the time before reserves are exhausted. It may be noted that total recoverable reserves are substantially larger than economically recoverable reserves, and also that the values presented in Table 2 do not include unconventional resources of oil and gas.

The virtually complete dependence of the transportation sector on petroleum is a singular phenomenon in the US energy picture. Whereas all other sectors have substantial ability to switch fuels in the event of a supply disruption, the transportation sector does not (*27*). World petroleum resources are concentrated in the politically unstable Middle East (*27,28*). Thus petroleum resources, and, in particular, the use of petroleum by the transportation sector, represent by far the major energy-security issues from a strategic point of view. Energy consumption by the transportation sector totaled 21 quads in 1988 (*13*), about a quarter of total energy consumption. Of this total, motor gasoline composed 14 quads, or about two-thirds.

Chevron (*29*) has forecast the future availability and price of petroleum well into the twenty-first century. These predictions are summarized in Fig. 2. According to Chevron, oil exploration and production are expected to become progressively more expensive. Thus the already prominent

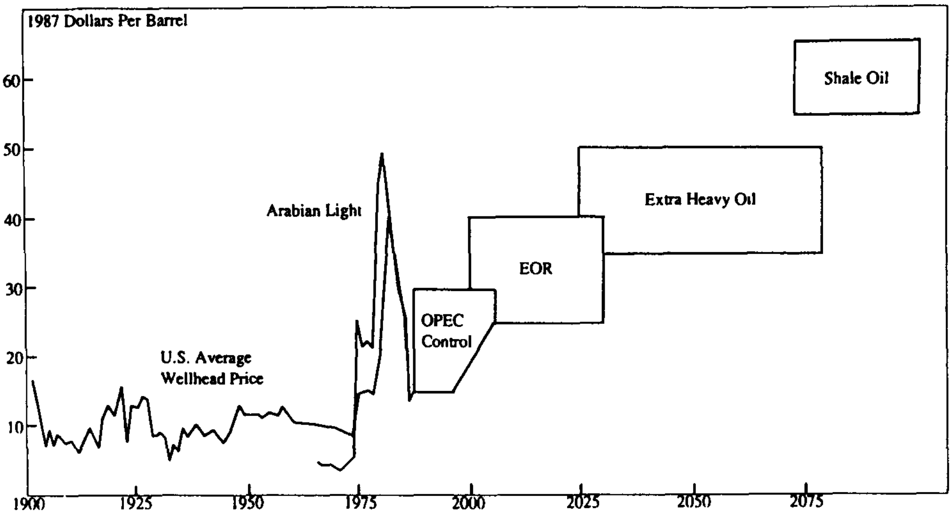

Fig. 2. Crude oil price outlook. Data from (*29*), ©Chevron Corporation.

role of petroleum in the national economy can be expected to increase significantly. Although the US is expected to import well over half its oil by 2000 (*27,28*)), with the bulk of this coming from OPEC (*27*), the era of OPEC dominance of world oil markets is expected by both Chevron and the DOE (*27*) to be with us for little more than another decade.

An additional major change is anticipated shortly after 2000, that of satisfying with other resources needs we presently meet with conventional petroleum. The shift from conventional petroleum is consistent with the distinctly limited size of domestic supplies (*see* Table 2). In the period 2000–2020, Chevron predicts that petroleum produced by enhanced oil recovery will be available at a price of 25–40 1987 dollars/barrel. This price prediction is consistent with the expectations of the American Petroleum Institute (*28*), which forecasts a price of 31 1987 dollars/barrel in 2000.

Present and anticipated oil prices provide a context in which to consider the selling price required for neat ethanol to compete with gasoline on a nonsubsidized basis for use as a transportation fuel. As presented in Table 3, the required wholesale selling price for ethanol is 46.2 cents/gal at today's oil and gasoline prices, and 76 cents/gal at the price predicted for 2000.

KEY ISSUES

In light of the discussion above as well as general considerations pertaining to fuel use, some key issues for the development of lignocellulose ethanol can be identified (*see* Table 4). For lignocellulose fuel ethanol to be viable, significant net energy must be available in the course of producing

Table 3
Required Price of Ethanol to be Competitive as a Neat Fuel

	Crude price,[a] \$/barrel	Wholesale gas price, cents/gal	Required ethanol price, wholesale, cents/gal[d]
1988	14.71	57.7[b]	46.2
2000	31	~95[c]	76.0

[a] 1988: from (*13*); 2000: from (*28*).
[b] From (*13*).
[c] In 1982, crude oil sold for 31.87 \$/barrel, and the wholesale gas price was 97.3 cents/gal (*13*). 95 cents/gallon is also consistent with the present increment of about 9\$/barrel as the added value of gasoline relative to crude oil.
[d] Based on an ethanol:gasoline equivalence ratio of 0.8 (*see* text).

Table 4
Key Issues for Fuel Ethanol Production from Lignocellulose

- Energetics of the lignocellulose/ethanol fuel cycle
- Fuel characteristics
- Air pollution and other environmental impacts
- Raw material supply
- Cost

lignocellulose and conversion to ethanol. Equally obvious is the fact that ethanol must be a good transportation fuel. Favorable impact with respect to air pollution and other environmental factors would make ethanol, or any other fuel, more attractive, whereas unfavorable impacts are strong disadvantages given the already high level of concern over this issue. A fourth key issue is whether enough raw material is available to make a difference. Finally, the issue of cost is inescapable.

TECHNOLOGY STATUS

Energy Balance

The energy balance for fuel-ethanol production from lignocellulose is not likely to constrain the development of this technology. Estimates for the energy required for lignocellulose production are typically about 15% of the energy content of the ethanol that could be produced therefrom with high productivity culture methods (*30–33*) and less for lower productivity methods. These estimates include energy required for planting, cultivation, fertilization, harvest, chipping, transportation, and, in one case (*32*), an allowance for equipment depreciation. Lignocellulose conversion to ethanol is similarly clear-cut. Combustion of unfermented residues, principally lignin, produces energy in excess of processing requirements for present process designs with a wood feedstock (*34*). Most designs make use of the excess energy to generate electricity in a cogenerative fashion. Because of the availability of lignin to provide energy for the process, theoretical conversion of carbohydrate is possible from an energetic perspective. The overall thermal efficiency of ethanol production from lignocellulose for a process with high yields is in the range of 45–60%, depending on the lignin content of the raw material.

The higher thermal efficiency of fuel ethanol relative to gasoline is discussed below. It may be noted here that the 20% greater thermal efficiency of ethanol implies that 1 quad of ethanol displaces 1.25 quads of gasoline. The added efficiency of utilizing the fuel ethanol compensates for the 15% energy loss in lignocellulose production.

Fuel Properties

The role of alcohol as a transportation fuel began with its use in the invention of the internal combustion engine by Nikolas Otto in 1897 (*5*). Alcohol fuels are different from, and in many respects superior to, gasoline as a fuel for spark-ignited engines (*16,35,36*). Ethanol has fuel properties very similar to those of methanol (*36–38*). Combustion of ethanol in internal combustion engines designed for alcohols will give higher thermal efficiency and power than use of gasoline in present engines, whereas performance is generally comparable to gasoline in nonoptimized engines (*35–38*). A significant development for the use of alcohol fuels is the fuel-flexible vehicle (*27,36*), which is capable of operating on any mix of ethanol, methanol, or gasoline. Table 5 summarizes performance parameters for fuel ethanol relative to gasoline. Problematic cold starting and fuel maldistribution are generally thought to require some modification but to be small issues, particularly for alcohol-devoted engines (*36,36,41*).

The thermal efficiency of fuel-ethanol utilization is a particularly important aspect of engine performance. Efficiency, along with energy density, determines the volume of ethanol required to deliver the same work as a gallon of gasoline, and hence the required price at which ethanol becomes competitive relative to gasoline. A range of thermal efficiency improvements for neat ethanol fuels relative to gasoline are frequently quoted (*10,27*), with typical values of 10–20%. Values are often cited without specifying whether the engine is designed for alcohols. Comparison is further complicated by the variability of gasoline and the sensitivity of efficiency to operating variables. Kampen (*12*) estimates volumetric fuel consumption for ethanol-devoted engines at 1.25 x that of a gasoline engine to travel the same distance, this implying that 1 gal of ethanol is equivalent to 0.8 gal of gasoline in terms of its ability to do work. This corresponds to a 17.6% greater thermal efficiency (using energy density ratios given by Kampen). Bernhardt (*11*) states that an optimally designed alcohol vehicle would have about 75–80% of the energy requirement of a vehicle designed

Table 5
Performance Parameters for Fuel Ethanol Relative to Gasoline[a]

Parameter	Effect	Property giving rise to effect	Reference
Equivalence ratio[b]	Lower	Lower lean flammability limit	(*12,37,39,40*)
Compression ratio	Higher	Higher octane	(*12,37,39*)
Thermal efficiency	Higher (10–20%+)	Chemical properties[c] leaner a/f ratios higher compression ratios	(*11,12,35,37*)
Cold starts	Difficult	Higher heat of vaporization	(*35*)
Fuel maldistribution	Increased	Higher volumetric flows, Higher heat of vaporization	(*35*)

[a] Statements are for neat ethanol in an engine designed for this fuel. Some benefits may cancel or diminish others. For example higher compression ratios increase efficiency while also increasing NO_x emissions (*35,38*).

[b] Equivalence ratio = (stoichiometric air-fuel ratio)/(actual a:f ratio).

[c] Increased efficiency is observed without changing the equivalence ratio or the compression ratio (*37,39*). This arises primarily from higher heats of vaporization and faster flame temperature, (*35*).

for standard gasoline, or 80–85% of the energy required for high-test gasoline. These values correspond to thermal efficiency increases of 25–33% relative to standard gas, and 17.6–25% relative to high-test. In terms of price, Bernhardt estimates that pure ethanol is equivalent to high-test gasoline at an ethanol price that is 75% of the gasoline price on a mass basis. This corresponds to 81% on a volume basis (gasoline mass density from [*28*], gas and ethanol energy densities based on the lower heating values given by [*10*]), implying a 24.4% higher thermal efficiency, and agrees very well with Kampen's evaluation.

Research has proceeded more rapidly on methanol utilization than on ethanol utilization of late (*16,36*), primarily because of the availability of inexpensive methanol produced from natural gas. Ford (*36*) has found volumetric mileage for methanol to be 0.6–0.7 x that of gasoline. This corresponds to methanol having a 25–46% higher thermal efficiency. These high efficiency increases are consistent with values presented by the EPA for fuel-efficiency increases for methanol relative to gasoline. Gray (*42*) reports small efficiency increases for the use of methanol without modification and for making the engine smaller because of increased power, a further efficiency increase of up to about 17% for compression ratio increases, an efficiency increased up to a total of about 27% if lean combustion is also employed, and finally an efficiency increase of up to about 45% made possible by fuel dissociation. Based on older work (*12,37*), efficiency increases possible with ethanol are approximately two-thirds to three-quarters of those possible with methanol.

Table 6
Emission Parameters for Fuel Ethanol Relative to Gasoline[a]

Parameter	Effect	Property giving rise to effect	Reference
NO_x	Equal or lower	Lower combustion temperatures, leaner a/f ratios	(*12,16,37,38*)
CO	Equal or lower	Leaner a/f ratios	(*16,37*)
VOC, evaporative	Lower	Lower vapor pressure	(*38*)
VOC, exhaust	Similar or higher amounts, higher aldehydes, lower photochemical reactivity	Many	(*37,38,43,44*)

[a] Statements are for neat ethanol in an engine designed for this fuel. Some benefits may cancel or diminish others. For example higher compression ratios increase efficiency while also increasing NC_x emissions (*35,38*).

Use of alcohols in compression-ignited diesel-type engines has been investigated to a smaller extent than spark-ignited engines; use in jet engines has not been studied at all to the author's knowledge.

Impact on Local and Global Air Pollution

Table 6 presents the anticipated effect of fuel-ethanol utilization on emissions of important pollutants. As with performance, evaluation of emissions is complicated by the dependence on operating variables. The only class of pollutant emissions significantly higher for alcohol fuels is aldehydes, which alcohol fuels produce in amounts 3–6 x larger than does gasoline (*44*). Several sources are optimistic about the use of catalytic converters to remove aldehydes and unburned fuel (*10,35,42*); however, Ford (*36*) is more cautious.

Notwithstanding the uncertainty over aldehyde emissions, the EPA (*38*) believes that significant long-term environmental benefits are available from using ethanol, and also methanol and compressed natural gas, as pure fuels in engines designed to take full advantage of the excellent combustion properties of these fuels. Table 7 presents estimated emission-reduction potential for alcohol fuels in light-duty vehicles. The prospect of emission reductions of this magnitude has been sufficient motivation for the state of California to give very serious consideration to the widespread substitution of methanol for gasoline (*45,46*). The choice of methanol was decided on the basis of current economics, rather than performance or emissions (*36,38*). Although methanol can be produced thermochemically from biomass (*47*), economics strongly favor production from natural gas.

Table 7
Estimated Emission Reduction Potential
for Alcohol Fuels in Light-Duty Vehicles[a]

Technology	Estimated emission reduction potential		
	VOC	CO	NO_x
Current (FFV)	20-50%	0	0
Advanced[b]	85-95%	30-90%	0

[a] Data from (*16*) for vehicles meeting current standards, and operated on *methanol.* Presentation with reference to "alcohol fuels" is justified because EPA "believes that the use of pure ethanol as a motor fuel would offer the same type of emission benefits as methanol" (*38*).

[b] Advanced technology refers to engines designed for alcohol fuels.

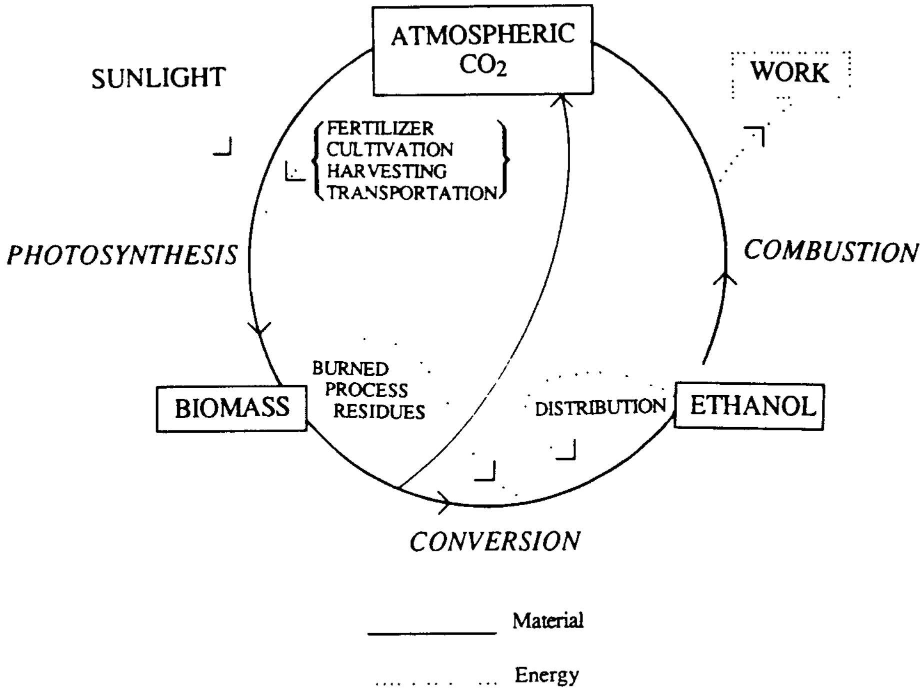

Fig. 3. Material and energy flows for production and utilization of fuel alcohol from biomass.

The lignocellulose-fuel-ethanol cycle is represented in Fig. 3. The cycle results in the net conversion of solar energy to engine work, and can result in no net generation of CO_2 (*14*). The release of CO_2 upon combustion is exactly balanced by the removal of CO_2 by photosynthesis. The stable cycle involving present-day photosynthesis, lignocellulose conversion to ethanol, and ethanol combustion can be contrasted to the situation

Table 8
Estimated Ethanol Production Potential from Waste Materials[a]

Waste source	Ethanol production potential	
	Quads	% total
Agricultural	1.9	37.9
Forestry	1.6	31.3
MSW	0.6	11.8
Other	1.0	19.0
Total	5.0[b]	100

[a] Values are estimated from sources giving data for collectible wastes compiled by Lynd (33).

[b] Individual potentials do not add to total potential, and do not correspond exactly to the % values, because of round-off.

for fossil-fuel combustion. Also the products of photosynthesis, fossil fuels originate from plant matter that accumulated incrementally over millennia. The relatively sudden release of this fixed carbon by fuel combustion over the course of about a century results in increased atmospheric CO_2 concentrations. The EPA draft report, *Policy Options for Stabilizing Global Climate* (23), recognizes the potential of biomass fuels to cut emissions of greenhouse gasses.

Raw Material Availability

Sources of lignocellulose can be divided into wastes from processes undertaken for a purpose other than energy production, and plants grown for the purpose of fuel production. The latter category may in turn be divided into conventional forestry and short-rotation intensive culture (*48*).

Table 8 presents estimates for the ethanol production potential from various sources of waste materials. The values given are based on estimates for collectible wastes compiled by the author (33). The total ethanol production potential from wastes is five quads, with about 38% of the potential from agricultural wastes, 31% from forestry wastes, 12% from urban wastes, and 19% from miscellaneous other wastes. The ethanol production potential is based on a process obtaining high yields from both 6-carbon (hexose) and 5-carbon (pentose) sugars with some allowance for processing losses, incomplete fermentation, and the production of microbial biomass. Details of the calculation procedure are in ref (33) and the legend of Table 12. The total of five quads as ethanol presented in Table 8 may be compared to the value of 13.8 quads of potential energy available as wastes given by Klass and Sen (*49*). These values are of comparable magnitude if the thermal efficiency of conversion to ethanol (discussed above) is taken into account.

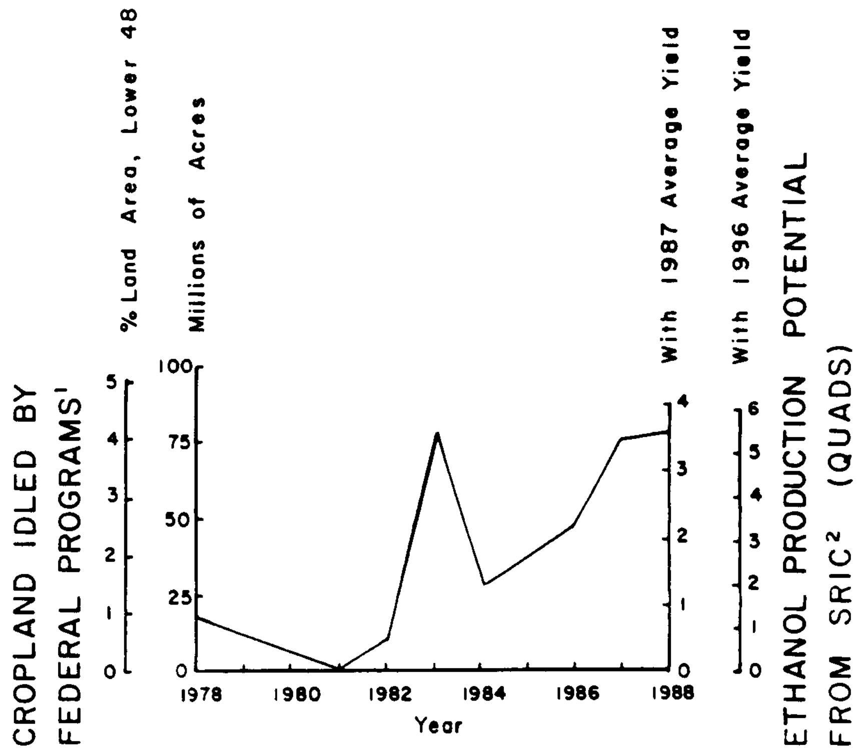

Fig. 4. (1) Land area and ethanol production potential for idled cropland. (2) Annual acreage reduction and conservation reserve programs data from (*49*). 1996 averge yields and biomass productivity from Ranney et al. (*31*); conversion yields from (*33*).

Utilization of some of the materials included in Table 8 would require development of technology beyond its present state. Currently available organisms are much less efficient at utilizing 5-carbon sugars, such as xylose, than at utilizing 6-carbon sugars (*34*). Xylose fermentation is discussed in detail below. A further point is that about two-thirds of the forestry wastes are softwoods (*10*), which are not as susceptible to biological attack as hardwoods (*50*). Whereas current research directions for efficient xylose utilization appear promising (*34*), utilization of softwoods may be a more difficult problem. Subtraction of softwood forestry wastes from the values presented in Table 8 would put the total waste potential at 4 quads.

Plants grown for energy production (energy crops) require allocation of land for this use. Categories of land that might be used for lignocellulose production include forestland that is not potential cropland, idled cropland, or potential cropland presently in other uses, which include some forests. Of these, idled land is by far the most variable. Figure 4 presents the amount of cropland idled by federal programs over the last 10 years and the amount of ethanol that could be produced from this land via short-rotation intensive culture and a conversion process with high yields. It may be noted that herbaceous energy crops grown in a one-year rotation are promising for short-rotation intensive culture (SRIC) (*31*). Such crops could be responsive to the widely varying amount of land in the idled cropland category. The ethanol production potential of idled cropland varies from 0 to 3.6 quads at present SRIC productivities, and from 0 to 5.6 quads at projected 1996 SRIC productivity.

Idled cropland results from the federal government paying farmers not to plant land under the auspices of the annual acreage reduction program and from the conservation reserve program (*52*). The land in these programs has amounted to over 4% of the land area of the lower 48 states during the last two years. Idled acreage in the conservation reserve program (CRP) was 31% of total idled land in 1988, the highest figure since the program's inception in 1986. The annual cost of the CRP alone was $3.8 billion in 1988. The CRP was created to convert highly erodible land to conserving uses (*52*). Ninety-five percent of the land enrolled in the CRP has been planted with grasses or trees (*52*), the two major energy crops considered for SRIC. Many lignocellulosic energy crops significantly reduce land erodibility relative to row crops (*31*). Although harvesting from land in the CRP is not presently allowed, Ranney et al. (*31*) note that SRIC crops would be an excellent compromise for obtaining economic returns from land while providing needed soil protection.

Table 9 presents land area requirements and ethanol production potential for various sources of lignocellulose. In addition to wastes and idled cropland already discussed, lignocellulose production by conventional forestry on forestland (excluding potential cropland) and SRIC on potential cropland are also considered. The values for forestland are based on the amount estimated to be available for energy production by the Office of Technology Assessment (*10*), which corresponds to 28% of commercial forestland. Values given for potential cropland are for the entire land in this category, with no allowance for availability. The ethanol production potential from wastes and all three land categories varies from 7.9 to 8.9 quads, with land devoted to unmanaged forests, and from 18 to 23.6 quads, with all suitable land used for SRIC with projected productivities. The variability in these values reflects that of idled cropland.

The ethanol production potentials listed in Table 9 are very large, several amounting to substantially more than the 14 quads currently used as motor gasoline. The overall potential is reduced significantly if SRIC is not employed. Although potential cropland may not become completely available for energy crops, this is not necessary in order that a very substantial contribution be made. For example, utilization of wastes, 50% of available forestland, 50% of potential cropland, and the mean idled cropland employing SRIC at projected productivities where possible would yield 15.4 quads on a total of 8.5% of the land area of the lower 48 states. In considering ethanol production potential and land requirements, it is

Table 9
Land Area Requirements and Ethanol Production Potential for Lignocellulose Sources

Source of material	Land area		Ethanol production potential, quads[a]			
	10^6Ha	% lower 48	Unmanaged forestry	Managed conventional forestry	SRIC, 1987 average productivity	SRIC, 1996 average productivity
Wastes[b]	None	None	5	5	5	5
Forestland[c]	39	4.9	1.1	2.2	-	-
Cropland[d]						
idled	0-32	0-4.1	0-1.0	0-1.9	0-3.6	0-5.6
potential	62	8.0	1.8	3.6	7.0	10.8
Totals[e]	101-103	12.9-17	7.9-8.9	10.8-12.7	14.2-17.8	18-23.6

[a] A fractional mass conversion of biomass to ethanol of 0.34 is used, which is equally applicable for trees and grass (*see* (*33*)). Values used for biomass productivity (Mg/Ha/yr) are as follows: unmanaged forestry, 3.4 (*48*); managed forestry, 6.66 (*10*); SRIC 1987 average, 13 (*31*); SRIC 1996 average, 20 (*31*).

[b] From (*33*).

[c] Land values are for forestland available for energy production excluding potential cropland. The data is inferred from (*10*) as follows: OTA estimates that the total net production potential of US commercial forestland is equivalent to 18-36 quads, and the total energy potential of this land is 5-10 quads, or 27.8% of the production potential. 27.8% of commercial forestland is 53 million Ha. The value of 39 million Ha is obtained by subtracting the 16.6 million Ha of potential cropland presently in forest (*51*) to avoid double-counting.

[d] Idled cropland from (*52*), potential cropland from (*51*).

[e] 2.2 quads is added to the last two columns, reflecting the contribution of managed conventional forests.

important to keep in mind the dynamic nature of present cropland requirements and energy use—neither of these is in any sense fixed. Cropland requirements could decrease substantially as a result of increased agricultural productivity or a shift in diet away from animal products. Approximately 80% of US cropland is presently used to produce animal feed (*53*). Alternatively, attractive export markets could increase cropland requirements for purposes other than energy production. Similarly, changes in transportation-fuel demand may well occur as the result of changes in fuel price, fleet efficiency, population, or driving habits (*54*).

Although the ethanol production potentials listed in Table 9 are very large, the same can be said of the land areas required. The author is not in a position to evaluate the full implications and likelihood of such major shifts in land use. A definitive analysis of this issue would certainly be welcome, but the ultimate answer may not come until we have experience with the environmental, economic, social, and other impacts associated with lignocellulose conversion to ethanol on a modest scale. It may be noted in passing that an amount of land corresponding to 29% of the area of the lower 48 states is currently leased for oil and gas exploration in these states (*28*).

Ethanol production from corn currently plays a significant role as a source of fuel ethanol and an alternative market for the agricultural sector

(*2–4*), and may well continue to do so into the future. However, the ethanol production potential of the entire US corn crop is an order of magnitude lower than the values presented in Table 9. Production of ethanol from corn at a volume commensurate with the current crop would be expected to saturate feed byproduct markets, upon which favorable economics depend (*10*).

Cost

In terms of the current state of technology development, the most critical cost issues concern conversion of the raw material to ethanol. Four main approaches have evolved for biologically converting lignocellulose to ethanol (*33,35*): separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), direct microbial conversion (DMC), and processes involving lignocellulose solubilization by acid hydrolysis. Acid-hydrolysis-based processes are considered to be less promising in the long term (*56*), and will not be considered further here. Flow diagrams for SHF, SSF, and DMC are presented in Figs. 5A, B, and C, respectively. The differences between these processes stem from the biological steps, and specifically the manner in which lignocellulose is hydrolyzed. SHF involves sequential enzyme production, hydrolysis, and fermentation, whereas SSF involves consolidation of hydrolysis and fermentation into a single step. DMC represents a further step in the direction of consolidation, in that production of the hydrolytic enzyme cellulase, lignocellulose hydrolysis, and fermentation to ethanol all occur in a single vessel. DMC is distinguished from the other processes in that cellulase production and fermentation are carried out by the same organism.

Research on SHF and SSF processes is being pursued by the Solar Energy Research Institute (SERI) as well as others. SSF is currently favored over SHF processes by SERI and seems likely to remain so (*55*). DMC processes are the least well-developed, but have the lowest potential cost, at least on a conceptual level. Advantages of DMC processes include no diversion of substrate for enzyme production, no added cost for enzyme production, and compatible enzymes and fermentation systems. Although the cost advantages of the properties of DMC systems are very significant (*33*), detailed cost analyses at the level of those available for SSF and SHF have not been performed for DMC. Two approaches are promising for development of DMC processes: 1) to broaden the substrate range of good ethanol producers, such as yeast or *zymomonas mobilis*, using recombinant DNA techniques; or 2) to improve the ethanol-producing ability of organisms with broad substrate ranges, such as thermophilic bacteria, using metabolic and/or genetic manipulation.

Table 10 presents the author's estimates of the stage of development for the various steps in the conversion of lignocellulose to ethanol. The least well-developed steps are the biological steps, whereas utilities and waste treatment are the most-developed steps.

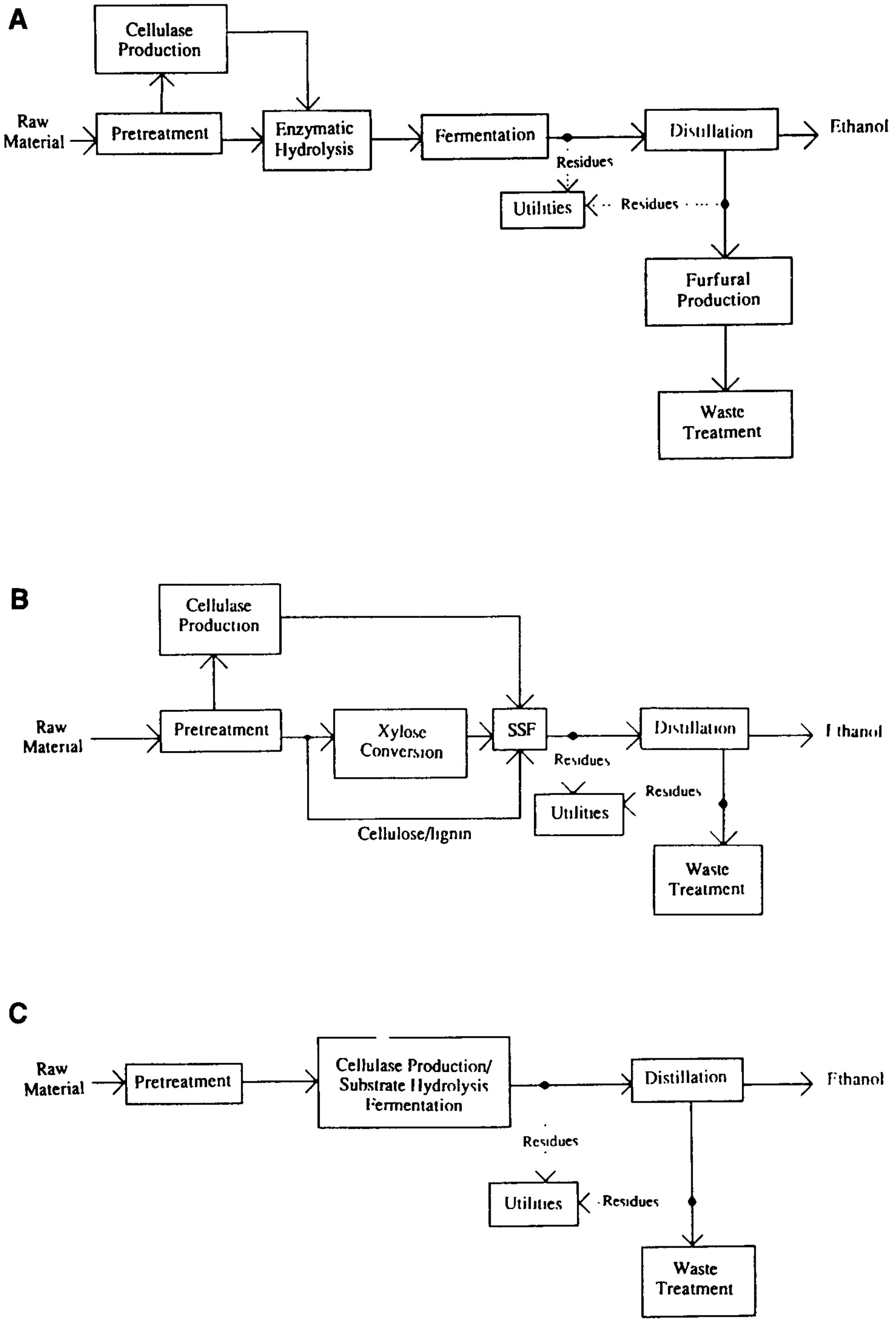

Fig. 5. Flow diagrams for processes producing ethanol from lignocellulose: (A) Separate hydrolysis and fermentation, adapted from (57); (B) Simultaneous saccharification and fermentation, adapted from (34); (C) Direct microbial conversion.

Table 11 presents economics for SHF and SSF process designs according to SERI. SSF has an 88 cent/gal cost advantage over SHF, primarily because the amount of enzyme required is reduced in consequence of lessened inhibition by hydrolysis products (*55*). Although xylose conversion systems are not very well developed, the incentive to utilize xylose and obtain high yields is so strong that substantial savings can be realized even with nonoptimal biocatalysts (*34*). A production cost of \$1.35/gal ethanol through an SSF process utilizing xylose represents the present state of the art. In 1980 the price was almost \$4/gal (*4*), and progress has been more rapid of late. A wholesale selling price of 0.60 1987 dollars/gallon is projected by SERI, based on current research directions and a low-lignin feedstock. SERI estimates that technology consistent with this price could be realized at the pilot scale by the year 2000 given an aggressive research and development program (*59*). Comparison of ethanol selling prices with present and anticipated gasoline prices is complicated by the choice of economic parameters, in particular with respect to capital recovery. However, a process having a selling price of \$0.60/gal according to SERI's assumptions would be very likely to be competitive with gasoline at prices anticipated in 2000 (*see* Table 3). An interim stage of process development having an ethanol selling price of \$0.75/gal is itemized in Table 11 with respect to costs for wood, other operating expenses, and capital.

Table 11 also shows the dominant contribution of biological steps to the cost of production, and the correlation between reduced overall cost and reduced cost of biological steps. The economic importance of the biological steps (Table 11) together with their poorly developed status (Table 10) makes the biological steps good candidates for future cost reductions, and a logical priority for research. Contributions to improving biological steps are likely to come from both engineering and biological approaches. Ethanol yield, ethanol concentration, and volumetric productivity are important parameters in determining production costs. All three are profoundly influenced by properties of the biological system.

Ethanol yield (mass ethanol/mass raw material) is determined by several factors. These include

The substrate-utilizing capability of the fermentation system, e.g., with respect to xylose;
The end-product metabolism of the fermentation system, e.g., whether products other than ethanol are formed;
The ability of the cellulase to hydrolyze the raw material;
The ability of the pretreatment process to make the raw material accessible to enzymes;
The process design (e.g., DMC increases yield because substrate is not diverted to enzyme production); and
The raw material (e.g., softwoods are more difficult to convert than hardwoods).

Table 10
Estimated Stage of Development
for Steps in the Conversion of Lignocellulose to Ethanol

Process step	Research			Pilot	Commercial
	Fundamental	Applied	Prepilot		
Biomass production	**	*	*	**	**
Pretreatment	*	**	**	*	*
Enzyme production	*	**	*		(*)[a]
SSF	**	**	*	(*)	
Xylose fermentation	**	**			
DMC	**	*			
Distillation		*	*	*	*
Waste treatment					*
Utilities					*
Residue processing				*	*

* = Some activity.
** = Major focus of activity.
[a] Cellulase is produced commercially, but commercial development has focused on applications other than hydrolysis for fuel production.

Table 11
Economics of Recent Process Designs for Ethanol Production from Lignicellulose

	SHF (1986)[a]	SSF (1988)[c]	SSF+Xylose (1989)[c]	SSF+Xylose Projected[d]
Cost of production, $/gal				
Wood	0.82	0.68	0.52	0.29
Other operating	0.79	0.48	0.39	0.25
Capital	1.05	0.62	0.44	0.22
Total	2.66	1.78	1.35	0.75
Steps with largest cost *relative to cost of production*				
Biological (enzyme production, hydrolysis, and fermentation)	55%	33%	29%	
Next largest (utilities)	14%	18%	12%	

[a] From Wright (*55*), based on results of Wright et al. (*58*).
[b] From Wright (*55*).
[c] From Hinman et al. (*34*) and N. D. Hinman (personal communication).
[d] From N. D. Hinman (personal communication), based on improvements from current research thrusts and a low-lignin feedstock.

Table 12
High Ethanol Yields for Biological Processing of Lignocellulosic Substrates Depend on Pentose Utilization[a]

Raw material	Hexan		Pentan		Total Sugars	
	Wt %	Potential Ethanol Yield[b]	Wt %	Potential Ethanol Yield	Wt %[c]	Potential Ethanol Yield
Corn	72	33.8	0	0	80.0	33.8
Hardwood	53.3	25.1	18	8.7	79.7	33.8
Forage grass	42.0	19.7	30	14.4	80.8	34.1
MSW	37.6	17.7	16	7.7	60.0	25.4

[a] Data from sources compiled in (33).

[b] Potential ethanol yield/unit lignocellulose is calculated as follows: yield/lignocellulose, $Y_L = TSF \times f \times Y_E$. Where TSF = total sugar fraction = (180/162)*fraction hexan + (150/132)* fraction pentan, which allows for the water of hydrolysis, f = fraction of total sugars fermented, which may be <1 due to either processing losses or incomplete fermentation. Y_E = ethanol yield per sugar fermented. The ethanol production potential is calculated assuming that $f = 0.9$, and $Y_E = 0.47$. The theoretical value of Y_E is 0.51; however, cell production typically lowers this somewhat.

[c] Total sugars are not the sum of the hexan and pentan fractions because of the water of hydrolysis (*see above*).

Cost sensitivities have consistently been shown to be greater for yield than for other parameters (*55,58*). This arises because the influence of yield is pervasive. Process steps affected include all aspects of substrate production, pretreatment, and fermentation, utilities, and waste treatment. Certain fixed costs associated with each of these steps are typically related to the amount of material processed, rather than the amount of product made, thus the amount of product made can be increased with little incremental expense. Critical issues with respect to ethanol yield are pentose utilization, elimination of fermentation byproducts (for DMC), improving conversion of softwoods, and utilizing lignin.

High yields from xylose and other 5-carbon (pentose) sugars is in all probability a requirement for an economic process implemented on a large scale. Table 12 presents data for the carbohydrate composition and potential ethanol yield for corn and representative lignocellulosic raw materials. If xylose, which exists in insoluble form as pentan, in converted, then corn, grass, and hardwood have virtually the same ethanol yield. In the case of forage grass, the contribution of pentan to the overall ethanol yield is 42%. Pentan also makes a very significant contribution (30%) to the potential yield from municipal solid waste. Typical yield values are 85–90% of theoretical for cellulose, and 70% of theoretical for xylose (*34,55*).

The ethanol concentration that can be practically achieved in the fermentation system is determined by the tolerance of the fermentation system, the tolerance of cellulase to ethanol and sugars (the latter limits ethanol concentration in SHF designs (*55*)), the limited concentrations of lignocellulosic slurries, and the distillation system. Rheological constraints limit lignocellulose slurries to about 12% (wt) carbohydrate, which even with theoretical yields, would produce 6% (wt) ethanol. Higher ethanol concentrations could be obtained, if tolerance permitted, by fermenting pentoses as well as hexoses. Ethanol concentration is an important issue primarily in relation to the fermentation and distillation steps. Continuous removal of ethanol from the fermentor can limit the effects of concentration to the distillation system (*33*). The sensitivity of distillation costs to ethanol concentration will depend on the distillation system employed. Typical ethanol concentrations are 4.5% for SSF (*55*), 2.25% for SHF (*55*), and 1.5–2% for DMC (*33*). These values are in the cost-sensitive region for nearly all distillation technologies, and may be compared to 7% or more for ethanol production from corn (*60*). Energy-efficient processes employing heat pumps and/or columns linked in a multieffect manner have been proposed (*61–63*). These can decrease the concentration sensitivity to distillation costs and energy requirements. Because distillation requires steam, utility-related costs are affected by ethanol concentration as well as costs for fermentation and distillation. Critical issues concerning concentration are understanding the cell biology of ethanol tolerance, and increasing research and full-scale experience with energy-efficient distillation processes and continuous ethanol removal.

Volumetric productivity (mass ethanol/bioreactor vol/X time) is determined by the rate of substrate utilization by cellulase (the primary factor for the insoluble raw material fraction), the rate of substrate utilization by the fermentation system (the primary factor for the soluble fraction), the ethanol concentration, and the bioreactor design. Primary economic impacts are on the saccharification/fermentation steps and utilities. A substantial portion of total energy requirements in current SSF designs is devoted to bioreactor stirring (*55*). Saccharification and fermentation are carried out in a batch reactor with a one-week cycle time (*55*). Productivities for both the saccharification/fermentation step and for xylose conversion are exceedingly low, at 0.27 and 0.17 g ethanol/L-hr, respectively. These values may be compared to conventional process for ethanol production from 6-carbon (hexose) sugars, about 3 g/L-hr (*3*), and high-productivity processes that can achieve over 100 g/L-hr (*64,65*). The saccharification and fermentation step *per se* is the largest single cost, by more than a factor of two, in the entire SSF process. Thus both the incentive and the potential improvements in the productivity area seem particularly significant. A promising approach is reactor design for conversion of lignocellulosic substrates. This is an understudied and underexploited area, in the author's opinion, perhaps in part because SERI's designs did not include fermentation in the presence of solids until the adoption of SSF in 1988. Progress in reactor design will probably involve continuous processing, and may also include differential retention and/or plug-flow distribution of raw material within the bioreactor. The potential of continuous processing is suggested by preliminary results in the author's lab (*66*), in which high hydrolysis yields are obtained from pretreated hardwood in a 12-h residence time using a simple well-mixed continuously fed reactor.

SUMMARY AND CONCLUSIONS

Of the major energy sources used in the US, petroleum is used in the greatest amount, and has the smallest domestic supply and greatest reliance on imports. The transportation sector accounts for roughly two-thirds of petroleum consumption in the US, has far greater dependence on petroleum than other energy sectors, and has the least flexibility to switch to alternative fuels. In addition, use of petroleum-based transportation fuels is a factor contributing to local air pollution and greenhouse-gas emissions. These factors make providing for future transportation fuel demand a particularly critical aspect of national energy planning and environmental protection. Energy balance considerations, fuel suitability, and anticipated air quality impacts are all consistent with the use of neat ethanol as a large-scale transportation fuel.

Projected ethanol production costs based on current directions of research would allow neat ethanol to be competitive with gasoline by the year 2000, according to current oil price predictions. In spite of a decade of intensive research, conversion of lignocellulose to ethanol must be regarded as a moderately well-developed technology, at best. Aspects of process configuration, biocatalyst selection, and other basic issues are still very much in a state of flux. The potential cost reductions through research-driven technological improvements appear to be great. Examples of research directions that are particularly likely to be productive are reactor design for systems accomplishing the hydrolysis and fermentation of solid substrates, more efficient utilization of xylose, and development of direct microbial conversion systems. Substantial cost savings are also available at the development level, for example, minimization of mixing-energy requirements in a saccharification/fermentation reactor.

If favorable economics allow the growth of a large-scale lignocellulose-based fuel-ethanol industry, a number of beneficial effects can be anticipated. These include a more favorable foreign trade balance; enhanced energy security; improved urban air quality; reduced emissions of greenhouse gasses overall, with no net emissions from that portion of the transportation sector powered by ethanol; and a major new crop for an agricultural sector that has been depressed for most of a decade and has more productive capacity than can be supported by present demand.

Ethanol production levels appear unlikely to be limited by raw material availability, as long as the economic and other factors are sufficiently favorable to justify allocaton of land for this use. Continued development of SRIC technology is highly desirable in order to minimize land requirements for raw material production.

Several applications other than neat fuel production, with significant impacts in their own right, can serve as proving grounds for processes converting lignocellulose to ethanol. These include coproduction of ethanol with other chemicals, use of ethanol as a chemical feedstock, and producing ethanol as a byproduct in the treatment of the nonplastic organic fraction of municipal solid waste.

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