THE POTENTIAL OF BIOMASS FUELS IN THE CONTEXT OF GLOBAL CLIMATE CHANGE: Focus on Transportation Fuels*

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■ **Abstract** An ultimate limit on the extent that biomass fuels can be used to displace fossil transportation fuels, and their associated emissions of CO_2, will be the land area available to produce the fuels and the efficiencies by which solar radiation can be converted to useable fuels. Currently, the Brazil cane-ethanol system captures 33% of the primary energy content in harvested cane in the form of ethanol. The US corn-ethanol system captures 54% of the primary energy of harvested corn kernels in the form of ethanol. If ethanol is used to substitute for gasoline, avoided fossil fuel CO_2 emissions would equal those of the substituted amount minus fossil emissions incurred in producing the cane- or corn-ethanol. In this case, avoided emissions are estimated to be 29% of harvested cane and 14% of harvested corn primary energy. Unless these efficiencies are substantially improved, the displacement of CO_2 emissions from transportation fuels in the United States is unlikely to reach 10% using domestic biofuels. Candidate technologies for improving these efficiencies include fermentation of cellulosic biomass and conversion of biomass into electricity, hydrogen, or alcohols for use in electric drive-train vehicles.

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1. INTRODUCTION

1.1 Overview

This review examines the role that fuels from renewable biomass might play as a strategic option to address concerns of climate change by replacing fossil fuels, and thus the CO_2 that is emitted when they are used. In principle, biomass-based fuels need not be a net source of CO_2 emissions because CO_2 released during combustion would be cycled back into plant materials by photosynthesis. However, energy is also required to cultivate, harvest, and process biomass, and the source of this energy, and its associated CO_2 emissions, must be considered in assessing the true potential of biomass to limit CO_2 emissions. Production and use of biomass also requires land, and the resource of available land must be considered in assessing the ultimate potential of biomass fuels on a global scale. This review focuses on the potential scale of biomass as a substitute for fossil fuels in order to offset CO_2 emissions, particularly on the role of biomass as a substitute for petroleum-based

transportation fuels. We pay particular attention to the systems in current, large-scale application (i.e. for production of ethanol) and their processes and process efficiencies. We introduce alternate fuel delivery systems and the opportunities for improving the net process efficiency for delivery of transportation fuel from biomass, and hence for lower net emissions of CO_2. We do not focus on the potential near-term commercial viability of biomass but envision that public policy factors might influence the penetration of biofuels if, for example, concern about global climate change leads to policies to limit atmospheric emissions of carbon dioxide.

Biomass fuels utilize the chemical energy fixed by photosynthesis and stored within plants. This chemical energy can be released to create heat for traditional purposes (such as cooking and space heating) or to produce industrial process heat (common in the paper industry), or it can be converted to electricity or to gaseous or liquid fuels (methane, hydrogen, alcohols, or oils). To displace the roles that petroleum-based fuels currently play in transportation would require significant conversion of biomass to liquid fuels, to fuels for use in fuel cells, or to electricity (which could potentially then be used to power electric cars). The conversion of biomass to electricity is conceptually similar to the conversion of coal to electricity, and it has been accomplished by similar means (direct combustion or gasification). Biomass is currently converted to liquid fuels by fermentation of carbohydrates to ethanol, or by extraction and refining of plant oils. There remain significant challenges to the conversion of biomass to liquid fuels: Only a fraction of the plant is used in current technologies, and significant energy is consumed in producing and processing biologically derived fuels.

Whereas overcoming these challenges could improve the overall efficiency of a biomass energy system and reduce the cost of biomass fuels, biomass energy's overall requirement for land would remain an issue if it were to be produced on a scale comparable to current fossil fuel production. Creation of biomass requires sunlight, water, nutrients, and land (or possibly ocean cultivation in the long run). Sunlight is a diffuse energy source, reaching the Earth's surface with an average energy density of roughly $180 \, W \, m^{-2}$ (annually averaged over the entire Earth's surface). The maximum potential photosynthetic conversion of sunlight to chemical energy is about 6.7%, although on average only 0.3% of the energy of sunlight falling on land is stored as carbon compounds in land plants. There seems to be significant room for selectively improving the use of sunlight to create biomass, perhaps including genetic engineering or intensive breeding programs. Important factors that will limit the extent of land available for future expansion of biomass production for energy include increases in world population; competition for land among agriculture, grazing, forestry, settlement, and parks; and preservation of natural ecosystems for biodiversity and recreation. The future availability of land for biomass energy will depend in part on land suitability; the extent of crop yield increase for food, timber, and fiber crops; and the availability of water. All of these will certainly vary by region.

Fossil fuels are a mainstay of the current global economy. Biomass supplies 14% of current global primary energy and will continue to be used in the future.

The potential for expanded use of biomass energy, either for electricity or liquid fuels, will depend on the demand for the energy form, the economic viability, the technology for conversion, the availability of land, and public policy factors. We raise these important issues, but we focus on the efficiency with which solar energy can be converted into biomass-derived transportation fuels to displace fossil fuels and their associated CO_2 emissions.

1.2   Reduction of Carbon Dioxide Emissions by the Production of Biomass Energy

In response to the concern that increases in atmospheric greenhouse gases may lead to adverse climate change (for a recent review see 1), a number of proposals have been made to stabilize and ultimately reduce anthropogenic emissions of greenhouse gases. Most focus has been on reducing CO_2 emissions from the use of fossil fuels. They include calls for near-term efforts to increase the efficiency of energy use, to reduce energy use, and to switch from high-carbon to low- or no-carbon fuels. The Kyoto Protocol (1a) to the United Nations Framework Convention on Climate Change (UNFCCC), drafted in December 1997 but not yet ratified by sufficient countries to enter into force, calls on developed countries and countries with economies in transition to reduce emissions of greenhouse gases in the period 2008 to 2012 by an average of 5.2% with respect to their emissions in 1990. The Kyoto Protocol would not limit emissions from developing countries. Longer-term goals could require a much larger decrease in the use of fossil fuels. For example, the ultimate objective of the UNFCCC (article 2) is " ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system ... " (1b).

Although science cannot yet provide reliable guidance on what, if any, levels of greenhouse gas concentrations might be judged "dangerous," studies of the processes that control levels of atmospheric CO_2 make it clear that massive reductions in future global CO_2 emissions would be required to achieve stabilization of atmospheric CO_2 at levels even two or three times the pre-anthropogenic level. The 1998 concentration of CO_2 [367 parts per million (ppm)] corresponds to a 30% increase from its relatively stable concentration before the year 1765 (2). Models of the global carbon cycle suggest that CO_2 emitted to the atmosphere exchanges rapidly with carbon held in plants and carbon dissolved in the surface waters of the oceans. Carbon cycle models can be calibrated to produce reasonable agreement between estimates of past emissions and the observed build-up of atmospheric CO_2 while reproducing records of isotopic tracers (3). Fossil-fuel emissions thus appear to be responsible for most of the observed increase in CO_2 concentration. When these models are used to forecast, they predict that the buildup of CO_2 will continue unless emissions are reduced drastically (3). To limit greenhouse gas concentrations to levels below 550 ppm CO_2 equivalent (approximately twice the pre-anthropogenic level) would require emissions reductions equivalent to a phase out of all fossil-fuel emissions in developed countries by 2050, if developing country emissions continue to grow as expected (4). It is in

this context that we consider the potential of biomass fuels as a substitute for fossil fuels.

CO_2 is the primary focus of international negotiations to reduce greenhouse gas emissions. When greenhouse gases are tabulated in terms of their CO_2 equivalent emissions (5), CO_2 itself comprises 80% of the total emissions of greenhouse gases (not including land-use change and forestry) from the developed countries— i.e. countries listed in Annex I of the Kyoto Protocol. Currently, global anthropogenic emissions of CO_2 occur primarily from burning of fossil fuels (83%), changes in land use (15%), and production of cement and concrete (2%). Emissions from changing land use occur, for example, when a forest is cleared and the carbon content of the forest's biomass and soils is released, either rapidly through burning or over a longer period through decay. Tropical deforestation is estimated to result in an emission of 1.6 ± 1 GtC year^{-1} (1 GtC $= 10^{15}$ g carbon in the form of CO_2) averaged over the 1980s (3).

Fossil fuels are the dominant source of energy currently used by humankind. Global fossil fuel CO_2 emissions have increased from 5.5 GtC year^{-1} averaged over the 1980s, to 6.5 GtC year^{-1} in 1995 (6). Global oil consumption grew 3.7% from 1990 to 1995 to reach 3.2 billion tonnes of oil equivalent (1 toe $= 42$ GJ) per year, containing 2.7 GtC. Of the oil consumed in 1995, 28% was consumed in the form of gasoline (7), and this end use of oil resulted in emissions of 0.8 GtC. Emissions of CO_2 from public electricity and heat production grew 15.3% from 1990 to 1997 and contributed 32% of all CO_2 emitted from fossil fuels in 1997.

Producing useable energy from an energy source that has low carbon emissions would lead to lower global CO_2 emissions. Energy from biomass, as from fossil fuels, makes use of the chemical energy stored during photosynthesis. When biomass is oxidized, CO_2 is released, as it is from fossil fuels. However, if new biomass is grown, then the CO_2 can be recycled from the atmosphere by photosynthesis and the process repeated. If no externally produced energy was used for biomass cultivation, harvesting, and conversion and if there were no net loss in soil carbon there would be no net emission of CO_2 in a full biomass fuel cycle—from one harvest to the next. In practice, however, biomass (or some other non-CO_2-emitting energy source) must be utilized to satisfy those additional energy requirements if the entire system is to be CO_2-neutral in net emissions. To the extent that fossil fuels are used to run a biomass energy system, there will be net CO_2 emissions from the full biofuel cycle. If the growth and harvesting of biomass results in a continuing loss of carbon in trees, plants, and/or soil over time, a biomass fuel might have similar carbon implications to the extraction of fossil fuels. Of course, a low carbon-emission source of energy would only reduce total emissions if that source were used as a substitute for a higher carbon-emission source, rather than to augment total energy production.

Long-term (e.g. to the year 2100) scenarios that result in reduced CO_2 emissions often rely, at least in part, on an increasing role of biomass energy to displace fossil fuels (8–11). The penetration of biomass energy in these scenarios is based on assumptions about new technologies and on costs and incentives that are often not explicitly stated and that are not predictable far into the future. Assessments

that look at biomass energy with a narrow perspective frequently give seemingly contradictory views of its potential. For example, analysis of the ongoing progress in converting biomass to usable forms of energy sometimes gives the impression that biomass energy can be produced without the use of the Earth's finite resources (12), and other times makes it appear that the use of biomass to make liquid fuels consumes more energy than it produces (13, 14).

This review considers some of the potential forms, technologies, and resource requirements of biomass energy to analyze the potential to reduce net greenhouse gas emissions. For example, a fundamental resource requirement of land-based biomass energy is land. Biomass production will require large amounts of land if its energy is to displace a significant fraction of fossil fuel energy and CO_2 emissions. The quantity of land required would depend on the productivity of biomass production and the process yield of useful energy, in our case transportation fuels, per unit biomass. Conversely, the amount of land available and the efficiency with which sunlight can be converted to biomass fuels will determine the amount of fossil fuels that may be replaced. Figure 1 shows a diagram of a biomass energy system in which each step of the system, going from sunlight to usable energy, adds efficiency losses and affects the net emissions of CO_2 by the system. Because biomass energy is being considered as a strategic option to mitigate future CO_2 emissions, the technology that is ultimately applied might be significantly different from that currently practiced, for two primary reasons. First, better technology will become available. Second, a key objective of the future system would be to avoid CO_2 emissions; this is not an objective for which current systems are optimized.

In this review we consider the physical limits on efficiency of each step in a biomass energy system, make comparisons to the efficiencies currently achieved and practiced, and consider implications for the potential of biomass energy to supplant a significant fraction of fossil fuel use and CO_2 emissions. Although we discuss a variety of biomass energy products, our focus is on transportation fuels. We begin by discussing photosynthesis and primary biological products (Section 2), discuss conversion of these products to modern fuels (Section 3), characterize biomass energy systems (Section 4), describe the resources required to produce large quantities of biomass fuels (Section 5), summarize large-scale experiences to date (Section 6), present some long-term economic, policy, and technology considerations (Section 7), and look into what the next 30 years might offer (Section 8).

2. FIXATION OF ATMOSPHERIC CARBON DIOXIDE BY PLANTS TO MAKE BIOMASS

2.1 Photosynthesis

Oxygenic photosynthesis, the process catalyzed by green plants, algae, and some other photosynthetic microorganisms, is the foundation of the modern biosphere.
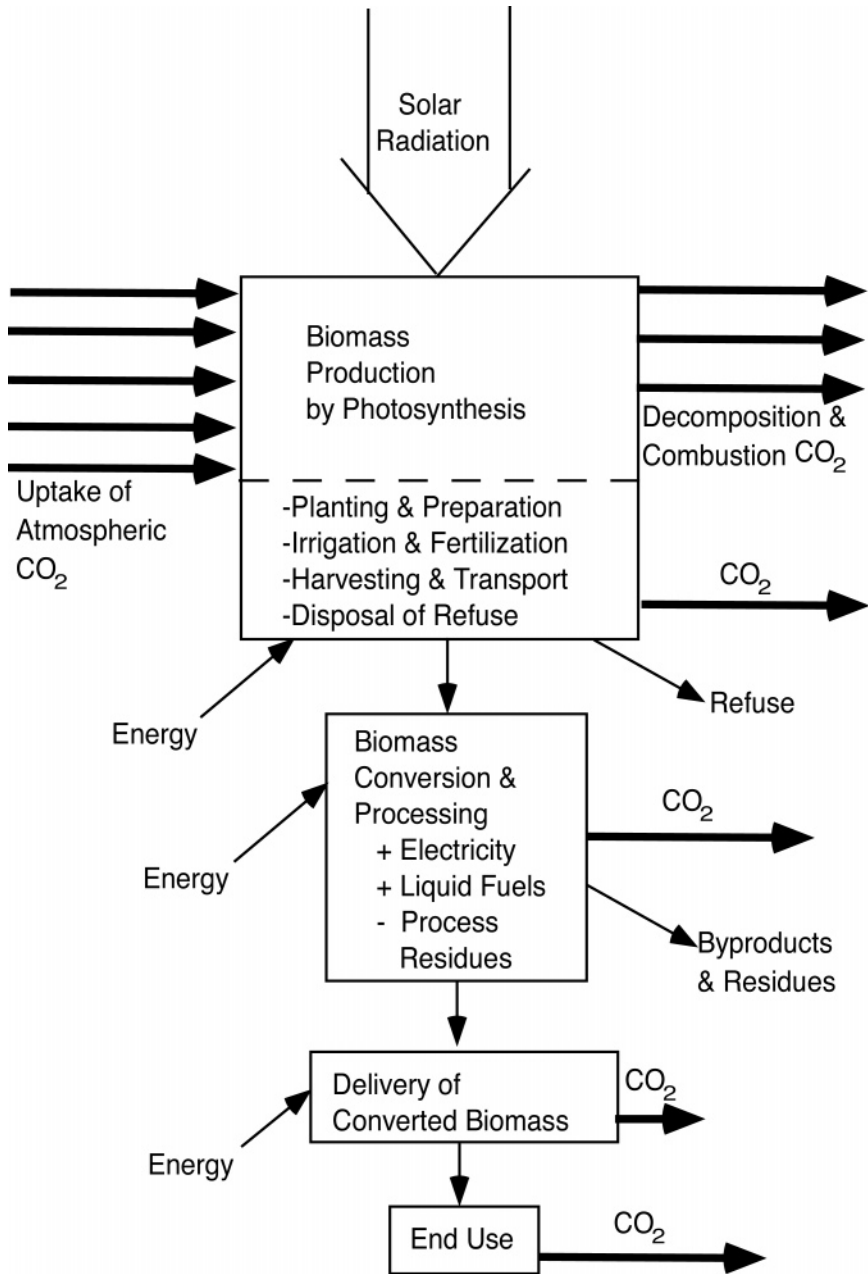
Figure 1 Schematic diagram of a biomass energy fuel system. CO_2 is sequestered from the atmosphere during plant growth. Various forms of energy may be used to run the biomass system; this energy might be a product of the biomass system or it might be supplied by other sources (fossil fuels, hydroelectricity, etc), which might contribute CO_2 emissions. CO_2 fixed as biomass is later emitted to the atmosphere as biomass refuse decays; process residues are used to produce process heat or animal feed, biomass is used to generate electricity, or biomass-derived fuels are consumed.

Figure 2 Schematic of the energetics of the light reactions of oxygenic photosynthesis. Two photochemical reaction centers, photosystems II and I, operate in series to remove electrons from water (to liberate oxygen) and to deliver them to NADP (nicotinamide adenine dinucleotide phosphate, a cofactor that serves as a source of reductant for reducing CO_2 to sugar. The vertical arrows indicate the conversion of the photoactive chlorophyll in the photosystems to the excited state, which then acts as a reductant. The chain of el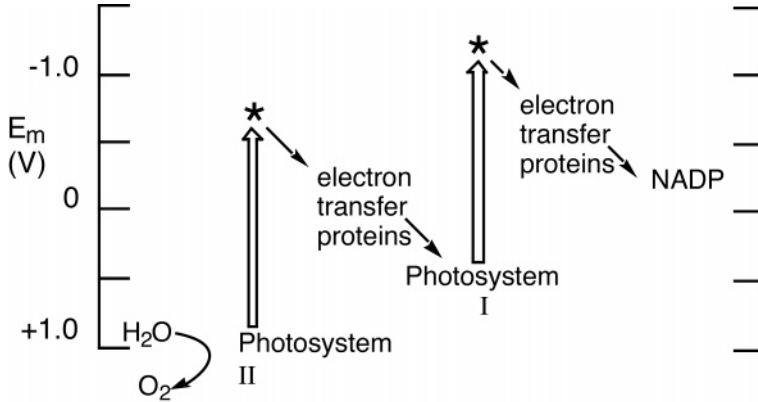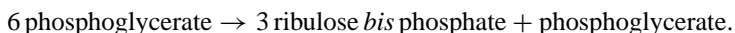ectron carriers between the photosystems catalyzes the generation of a transmembrane proton gradient that is used to generate adenosine triphosphate (see text), which is required to drive the CO_2-fixation reactions toward synthesis. Because the two photosystems are single electron devices, it takes four turnovers of each (i.e. eight quanta in total) to liberate one O_2 from water, and reduce two molecules of NADP. It takes two molecules of reduced NADP to capture one molecule of CO_2.

Oxygenic organisms possess pigment arrays of chlorophylls and carotenoids—known as photosystems I and II—that effectively capture incident sunlight. The sunlight generates an oxidized chlorophyll species and a reduced species, most likely a pheophytin, within these photosystems. The reduced species provides electrons to a chain of carriers that eventually reduce carbon dioxide to biomass while the oxidized chlorophyll is re-reduced by a system that takes electrons from water, liberating oxygen (Figure 2). Since the active pigments are chlorophylls, the effective energy of incident sunlight photons—maximal solar spectrum at 480 nm (249 kJ einstein^{-1})—is essentially degraded to the wavelength of the long wavelength band of chlorophyll, at approximately 700 nm (171 kJ einstein^{-1}). Under optimal conditions every photon arriving at a photosystem is used effectively and the quantum efficiency of photosynthesis is 1. However, optimal conditions are rarely achieved outside the laboratory and many photons are wasted by fluorescence and other processes. Even under optimal conditions it takes at least 8 quanta of energy to liberate an oxygen molecule. Each photosystem moves a single electron per turnover, and the oxidation of two water molecules to liberate a diatomic oxygen molecule is a four-electron process at photosystem II followed by four single electron turnovers at photosystem I.

Figure 2 presents a schematic of the energetics of oxygenic photosynthesis. The two photosystems operate in series to remove electrons from water and deliver them to NADP (nicotinamide adenine dinucleotidephosphate), a cofactor that serves as a source of reductant for reducing CO_2 to sugar (15). The oxidation of two water molecules to liberate one diatomic oxygen provides enough electrons to reduce two molecules of NADP, and it takes two molecules of reduced NADP per molecule of CO_2 consumed. Many electron transfer proteins are involved in this electron transfer pathway, and the net effect of electron transfer is to simultaneously pump protons across the chloroplast membrane as electrons move from water to NADP. The proton gradient is subsequently used to drive the phosphorylation of adenosine diphosphate to adenosine triphosphate. The reverse of this reaction, the hydrolysis of adenosine triphosphate to adenosine diphosphate, releases free energy needed to drive the reduction of CO_2 to sugar.

The primary CO_2-fixation reaction is catalyzed by the enzyme ribulose *bis* phosphate carboxylase, which carboxylates the five-carbon ribulose 1, 5 *bis* phosphate to a transient six-carbon intermediate that cleaves to two three-carbon moieties. These are manipulated by a suite of enzymes, operating in what is known as the Calvin cycle (16), to regenerate ribulose *bis* phosphate and save the fixed carbon so that it can enter cellular metabolism. It is perhaps easiest to see the overall stoichiometry if we consider three carboxylations in synchrony:

$$3 \text{ ribulose } \textit{bis} \text{ phosphate} + 3CO_2 \rightarrow 6 \text{ phosphoglycerate}$$

$$6 \text{ phosphoglycerate} \rightarrow 3 \text{ ribulose } \textit{bis} \text{ phosphate} + \text{phosphoglycerate}.$$

Thus, three molecules of CO_2 are effectively reduced to one molecule of phosphoglycerate. Two phosphoglycerates are in turn converted to the hexose glucose, so another way of looking at the overall reaction is

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2.$$
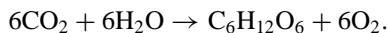
A corollary is that the fixation of each molecule of CO_2 results in the release of one molecule of O_2. There is good evidence that the atmosphere of our planet contained no significant free oxygen until the advent of photosynthetic water cleavage, so the fact that our atmosphere now contains some 20% O_2 gives an indication of the enormous amount of carbon that is trapped in fossil forms, and of the enormous impact that photosynthesis has had on our planet (17).

A major constraint to the Calvin cycle probably stems from the fact that the initial enzyme of the pathway, ribulose *bis* phosphate carboxylase, originated in the absence of oxygen. Under present atmospheric conditions, as much as 50% of the CO_2 initially fixed by the enzyme is lost in a process known as photorespiration, in which the enzyme adds an O_2 to ribulose *bis* phosphate instead of a CO_2 (18). The oxygenated product still cleaves following the reaction, but now into one three-carbon species and one two-carbon form, and the latter is eventually metabolized to CO_2 and H_2O. The net effect of this undesirable side reaction is thus to lose two previously fixed CO_2 molecules. Consequently, photorespiration

has a negative impact on net productivity. Significant research has been done in attempts to engineer the enzyme so that it no longer has this affinity for oxygen, so far without success. In fact, there is mounting evidence that the process serves a vital protective role against damage under bright light when CO_2 levels are low (19). One of the potentially beneficial effects of rising atmospheric CO_2 levels, at least from the perspective of plants, is that photorespiration should decrease, and so overall growth efficiency should increase. This phenomenon has been termed CO_2 fertilization (20).

Some 14 million years ago, several groups of plants, including the tropical grasses, developed a preconcentrating "retrofit" to the Calvin cycle, which significantly alleviated the photorespiration problem. These plants became widespread by 7 million years ago (21, 22). In these plants, CO_2 is initially added to a three-carbon acid to form a four-carbon species, and this is then transported to a special region of the leaf where the ribulose*bis*phosphate carboxylase is located. Here the carboxylation is reversed so that the local CO_2 concentration is enhanced, and photorespiration is dramatically decreased. Plants that have this retrofit are known as C_4 plants because the first radiolabeled intermediate that can be isolated when the plants are transiently provided with $^{14}CO_2$ is a four-carbon acid. Important agricultural examples are corn (*Zea mays*) and sugarcane (*Saccharum officinarum*). Plants without the retrofit are known as C_3 plants because in similar experiments the first intermediate isolated is the three-carbon phosphoglycerate discussed above. Whereas C_4 plants, especially the tropical grasses, are important in warmer ecosystems, some 95% of global plant biomass arises from C_3 photosynthesis; wheat, rice, potatoes and barley are important C_3 crops, and algae and most trees use C_3 photosynthesis.

Theoretical maximum efficiency of the photosynthetic process of converting solar energy into biomass in land plants has been estimated to be 3.3% for C_3 plants and 6.7% for C_4 plants (23). These rather disappointing numbers are the result of the combination of several factors. As discussed above, only about half of the energy of the photosynthetically active light is actually available to chlorophyll. For C_4 plants, only about 80% of this light is absorbed effectively, only 28% of this light energy is conserved in the energy in glucose, and then some 40% of this energy is used in the growth processes of the plant. Plants using C_3 photosynthesis do even more poorly, losing about 30% of their already fixed CO_2 by photorespiration, and "wasting" perhaps 30% of the available photons under high intensities. Maximal efficiencies are not achieved in practice because of, for example, inadequate water and auxiliary nutrient supplies, and the fact that most plants grow well in only some seasons of the year. The storage of energy in the form of biomass in crops and natural ecosystems thus occurs at a rate significantly less than the maximum theoretical efficiency for photosynthesis.

2.2   Global Net Primary Productivity

Net primary productivity (NPP) is the rate of storage of biomass or carbon in living plant matter. As a plant grows, its NPP passes through a maximum during its fastest-

growth stage. A mature, fully grown plant usually exhibits a lower NPP because new biomass is only required to replace dying parts of the plant (e.g. leaves). For the biosphere as a whole, averaged over time, NPP is near a steady state in which the rate of creation of biomass roughly equals the loss of living biomass as plants die.

The global plant biomass on land is estimated to be about 600 GtC, whereas the marine biomass contains only about 3 GtC. NPP, however, is rather more equally shared; about 60 GtC year^{-1} on land, and 50 GtC year^{-1} at sea (3). The ratio of biomass to NPP provides the average carbon residence time in plants; 1 month in the oceans, and 10 years on land. Of course, this is an average; for grasslands the residence time is roughly 3 years, whereas it is greater than 25 years in typical forests. Because the oceans cover 71% of the Earth's surface, the average NPP per unit area is much less in the oceans than on land.

The total productivity of the Earth's biosphere is significantly less than the maximum theoretical efficiency of the photosynthetic process of converting solar energy into biomass. The Earth's land masses span 15×10^9 hectares (ha) and the average NPP per area of the Earth's terrestrial biosphere is 4 tC ha^{-1} year^{-1} (400 gC m^{-2} year^{-1}), averaged over all land. This corresponds to an energy storage of 0.5 W m^{-2}, which is 0.3% of the 180 W m^{-2} average density of solar energy falling on the Earth's surface (24), an efficiency significantly less than the theoretical maximum of photosynthesis (3.3%–6.7%, see above). Some ecosystems, of course, have much higher NPP than the global average. Forests contribute about 40% of global terrestrial NPP and lead to large amounts of forest litter that serve as food for detritovores and maintain the carbon content of soils. In an extensive review of the literature, Grier et al (25) reported values of NPP of above-ground biomass in forests from 0.4 to 18.8 tC ha^{-1} year^{-1}. Plants in stable natural ecosystems are often close to maturity, having passed their rapid growth phase. This is in contrast to both food and energy crops, which are usually harvested during or soon after their rapid growth phase, leading to higher average NPP.

2.3 Potential Biomass Crops

Whereas much current biomass energy is derived as a by-product of other crops, energy production from biomass on a much larger scale will require "energy crops." The optimal energy crop will depend on the local biophysical conditions (climate, soil, topography, etc), resilience to disease, and the expected use of the crop. Two general types of energy crops have received the most attention in the United States for their future potential; short rotation woody crops and herbaceous crops (26). Typical examples of the former are poplar and willow, with eucalyptus in hotter regions. Switchgrass, energy cane, and sorghum are examples of herbaceous energy crops. Widespread use of these crops would require changes in agricultural and conversion technologies. The ethanol business in the United States today is based on corn starch, whereas other grains and sugarcane are used elsewhere (27), and oil crops such as rape and soy provide

a small fraction of European and US diesel fuel, respectively (28). The most productive areas of the United States for energy crops are in the central and southeastern regions. Johansson et al (29) suggested that on a global scale the largest amount of lands in developing countries suitable for biomass production and not needed for food production are located in sub-Saharan Africa and Latin America.

In current crops, only a fraction of the total biomass produced via photosynthesis is harvested. Nominally, a third of the NPP of a crop is translocated below ground. Of the above-ground biomass, only a fraction is harvested. For sugarcane, typically only the cane stem is harvested, not the leaves and tops, and this makes up about 53% of the dry above-ground biomass (30). Table 1 lists the typical harvested yields and composition of the harvested biomass for four crops. Each of these crops has been optimized to maximize economic yield of starch (corn), sugar (sugarcane), protein and oil (soybean), and wood (poplar). Currently, only the sugar and starch fraction of biomass is commercially fermented to make ethanol. The cellulose and hemicellulose fraction is also accessible to fermentation, although not currently on a commercial basis. All biomass, except ash, is pyrolyzable.

Biomass varies somewhat in both its energy and carbon content. In their assessment of biomass supply, Hall et al (23) used an energy content of 19.8 GJ dry-t^{-1} of hybrid poplar and 17.5 GJ dry-t^{-1} (1 t = 10^6 g) for other (herbaceous) crops (high heating values). As a recipe for calculating greenhouse gas emission inventories, the Intergovernmental Panel on Climate Change (IPCC) (31) used a default carbon weight content of 50% of dry biomass. Glucose, of course, has a carbon weight content of 40%, and polymers of glucose (such as cellulose) have a carbon content slightly higher. To facilitate comparisons, we use

TABLE 1   Crop yields and compositions[a]

Crop	Typical yield (t ha^{-1} yr^{-1}, % water content)	Biomass compositional yield (t ha^{-1} yr^{-1}, % of dry biomass)					
		Sugar & starch	Cellulose & hemicellulose	Oil	Protein	Lignin	Ash
Corn kernel	7.5 14%	4.9 76%	0.5 7%	0.3 4%	0.6 9%	0.2 3%	0.1 1%
Sugarcane stems	65 70%	9.1 47%	4.6 23%	0 0%	0 0%	3.3 17%	2.6 13%
Soybean	2.25 13%	0.2 13%	0.3 15%	0.5 23%	0.9 46%	0 0%	0 0%
Poplar wood chips	11.2 15%	0 0%	6.6 70%	0 0%	0.3 4%	2.2 23%	0.3 4%

[a]These values are our best estimates, derived from numerous sources that do not always agree in detail. They are thus estimates of averages that vary from region to region, and on what cultivar of crop is planted. The sugarcane numbers are based on data from Brazil, but they are reasonable for all regions. Other values are based on data from the United States.

a carbon weight content of 44% and an energy content of 40 GJ tC^{-1} (to give 17.6 GJ dry-t^{-1}) for carbohydrate materials and a carbon weight content of 50% carbon and an energy content of 20 GJ dry-t^{-1} for woody materials throughout this review.

Crop yields depend on a number of factors: the plants' NPP, the number of harvests per year, the fraction of plant biomass harvested, and the usable fraction of the harvest. Over the past several decades, there has been a continued increase in food crop yields. This increase in yields has been primarily due to increases in the usable fraction of the plant (e.g. the mass of corn kernels per mass of corn plant) rather than to increases in plant biomass production (NPP) (32). Current yields of some crops do surpass the most productive natural ecosystems. For example, in 1987, the worldwide average yield of above-ground dry biomass from sugar-cane, a C_4 plant that is probably the highest yielding, major land-based crop, was 36 dry-t ha^{-1} $year^{-1}$ (16 tC ha^{-1} $year^{-1}$) (23) with an energy content of 1% of incident sunlight. Average potential yields of short-rotation woody crops in the United States are thought to be about 14 dry-t ha^{-1} $year^{-1}$, and herbaceous energy crops are thought able to produce about 12 dry-t ha^{-1} $year^{-1}$ over wide areas (33). It thus seems unlikely that practical maximal efficiencies for recoverable terrestrial plant matter will exceed 2% of the incident sunlight.

2.4   Aquatic Plants

Land plants are not the only option for renewable biomass production. Marine algae, both microalgae (microscopic) and macroalgae (e.g. kelp), have been considered as potential renewable resources, either in the sea or on land using otherwise unexploited saline water in arid regions. Current estimates are that the annual microalgal productivity could be as high as 81 dry-t ha^{-1} $year^{-1}$ (36 tC ha^{-1} $year^{-1}$) if saturating levels of CO_2 were provided, perhaps from power station flue gases. Chelf et al (34) estimated that all the CO_2 emitted from fossil fuel power plants in Arizona and New Mexico could be captured by microalgae farms occupying only 0.25% of the state's area. Cultivated macroalgae are reported to have yields of up to 150 dry-t ha^{-1} $year^{-1}$ (35). Although these yields seem very high, it is possible that the yields might be significantly higher than for sugarcane under optimal conditions. Current estimates of costs, especially capital costs, are high, and today the commercial growth of macroalgae is for the production of agars and carrageenans, which are quite valuable—$1 billion per annum (36). The only large-scale exploitation of microalgae is for food additives (37).

2.5   Hydrogen-Producing Microorganisms

As discussed above, oxygenic photosynthesis splits water to release oxygen gas and uses the hydrogen atoms to drive the reduction of carbon dioxide to sugars. Under some circumstances, however, some microalgae and cyanobacteria are able to release the reductant as hydrogen gas. This phenomenon has been known for

almost a hundred years, and attempts to exploit it date from at least the early 1970s
(38, 39). If a successful process could be developed it would potentially provide a
supply of hydrogen from water.

There are substantial barriers before the trace amounts of hydrogen detected in
the laboratory can be developed to a significant energy source (39). Several av-
enues are being explored in the United States, Japan, and Europe. Perhaps the
simplest would be a single-stage direct photolysis reactor that produced oxy-
gen and hydrogen simultaneously, although the problems of safely separating
these gases should not be underestimated. Oxygen would still be evolved by
the water-splitting enzyme at photosystem II (Figure 2) and hydrogen would
be evolved by a hydrogenase enzyme accepting electrons from photosystem I.
Unfortunately, all the hydrogenase enzymes known from photosynthetic organ-
isms are exceptionally sensitive to oxygen, and development of this idea will
require the development of an oxygen-tolerant hydrogenase, perhaps by genetic
engineering.

Alternatively, the problem of separating oxygen and hydrogen might be finessed
by separating the two processes, either temporally in a single reactor or spatially,
with the two reactions occurring in different reactors. This would require that the
reductant produced in the light be stored as carbohydrate, and that this be the source
of hydrogen in a subsequent anaerobic dark reaction, or possibly in a photo-assisted
fermentation (38). The first reactor, for the growth of the photosynthetic organisms,
might be a simple "raceway" pond, but the hydrogen-generating reactors will of
course have to be enclosed.

Regardless of whether single or two-stage reactors are used, a major limita-
tion of the biological efficiency in such systems is that the photosynthetic or-
ganisms shade each other and the size of the photosynthetic antenna will have
to be reduced to effectively use full sunlight at reasonable cell densities
(e.g. 40).

Alternatively, some bacteria produce hydrogen from biomass under anaerobic
conditions (41, 42), although currently with low yield. Whether this can be devel-
oped to a useful technology, similar to that which produces methane from wastes
(see below), remains to be seen.

3. CONVERSION OF BIOMASS
TO ENERGY PRODUCTS

The use of biomass for energy could be extended if technology was used to convert
it into useful energy products with high efficiency. Modern technology could also
relieve the health and environmental problems inherent in the traditional uses of
biomass energy for cooking and space heating. The success of biomass energy
products will depend on the cost, resource requirements, and environmental and
socioeconomic impacts involved in producing energy services relative to those of

competitive sources. In this section we review existing and potential technologies for converting biomass into various modern energy products.

3.1 Electricity and Heat

Current systems that produce electricity from biomass burn it in air to produce heat, which is converted to mechanical energy via a steam turbine that generates electricity. Generation of electricity in this way is similar to conventional coal-fired generation. Installed biomass-fueled generating capacity in the United States was 10 GW in 1998 (42a). Regulatory incentives such as the Public Utility Regulatory Policies Act of 1978 aided the development of biomass-fueled capacity in the United States. This legislation requires a utility to purchase electricity from co-generators and other qualified independent power producers at a price equivalent to the utility's avoided cost (43). Biomass-fired electricity is produced primarily where there is an inexpensive source of biomass, such as waste products in the wood industry.

Existing biomass electricity generation using steam turbine technology exhibits low efficiency owing to the inherent inefficiency in the steam cycle, the water content of biomass (requiring either drying or burning of wet biomass), and the small size of biomass power plants relative to coal-fired power plants. Most biomass power plants operating in the United States today are characterized by net plant efficiencies in the range of 20%–25% [high heating value basis; (44)]. Lower values occur in situations where the fuel is a waste material that would otherwise present a disposal problem and there is no incentive to increase efficiency. The efficiencies of modern coal-fired power stations can exceed 40%, although the average efficiency, worldwide, of the installed stock is about 30% (8). There is potential for improved performance, for example by co-firing large generating facilities with biomass and coal, thereby avoiding the inefficiency caused by small power-plant size. This may be the simplest way for a significant use of biomass fuels in the United States in the near term. Local cogeneration of heat and electricity might offset energy inefficiencies in smaller plants (45, 46).

Alternatively, biomass can be gasified prior to conversion to electricity. Biomass is more reactive than coal and it contains much less ash and sulfur. However, it contains more nitrogen, which might lead to higher NO_x emissions. Biomass is an attractive fuel for advanced gasification-based power stations, especially in the case of pulp and paper waste or agricultural by-products such as sugarcane stover (43, 47). The presence of water in biomass feedstock need not be an efficiency detriment if the biomass is gasified. Biomass-integrated gasifier/gas turbine cycles are the focus of research, development, and demonstration efforts (43). Mann & Spath (48) describe a biomass gasification combined-cycle power system with a net plant efficiency of 37.2%. Efficiencies of 40% to 45% are hoped to be achievable (49, 50), comparable to those already achieved with advanced technologies with coal, although inferior to those achieved with natural gas (51). Additional

improvement may be achievable by producing electricity from fuel cells fed by a biomass-integrated gasifier. Fuel cell improvements would also contribute to the efficiency of fossil fuel power.

The direct use of solar energy to produce electricity by photovoltaics (or solar-thermal power generation) can produce electricity at much higher efficiencies (sunlight to electricity) than biomass systems. Photovoltaic efficiencies of 10% have already been achieved, and efficiencies of >25% may be practical in the future (52). This compares with a potential efficiency of roughly 0.4% for the conversion of, e.g. sugarcane to electricity (1% efficiency for sunlight to above-ground cane biomass times a potential 40% efficiency for conversion of biomass to electricity in a gasification combined-cycle power system). Therefore, the land use requirements of photovoltaics are significantly less than for a biomass system. Furthermore, photovoltaic systems would preferably be situated in dry, cloudless conditions and, therefore, might not compete directly with other land uses such as agriculture. Comparison of the direct efficiencies of conversion to electricity does not, of course, tell the full story. As detailed below for bioenergy sytems, there is ultimately a need to compare the full systems and the energy delivered from them. This would include the energy required to construct and maintain the systems, to compensate for the annual and diurnal cycles of photovoltaic systems (and hence the need for power storage or some other load-leveling source of power), and to incorporate other environmental and economic impacts and services. Currently, the capital cost for solar energy systems prevents their use for the production of bulk energy demand, and there are substantial design limitations in collection, storage, and distribution that must be overcome before solar energy can be effective for base load or peaking capacity.

Modern biomass fuel systems are also used to generate heat, both industrial process heat and for district heating systems. Again, these rely primarily on direct combustion and on low-cost fuel supplies such as those available in the forest products or agricultural industries. The problems and prospects are similar to those encountered in the power-generating systems described above.

3.2   Ethanol

Ethanol is used as a liquid transportation fuel, either blended with gasoline or in the form of hydrated ethanol, in internal combustion engines, and it may prove to be a useful fuel for fuel-cell powered vehicles. Interest in ethanol as a transportation fuel is driven in part by concerns about oil-supply security, trade balance and urban air pollution, and also by agricultural business interests.

The fermentation of starch and sugar to ethanol dominates the world market for this commodity. The fermentation of sugars to ethanol is a time-honored process that has been practiced for at least 5000 years (53). Using it as a fuel in the internal-combustion engine also has a long history (54). In 1996, Brazil produced 13.9 billion liters of ethanol (the energy equivalent of 136,000 barrels petroleum per day) from sugarcane (55). The Brazilian industry was apparently well integrated,

with some waste biomass being converted to methane (see below), fertilizer, and animal feed, and a sizable chemical industry that used some 723 thousand tons of ethanol in 1989 (56). Nevertheless, it relied on subsidies for profitability, and when these were reduced in 1990, the future of the industry became unclear (55). Moreira & Goldemberg (55) suggested that there are good prospects for reducing the costs of cane-derived ethanol to 0.12\$ liter^{-1} (the equivalent of about \$20 per barrel oil), but nevertheless characterized its potential for reducing net emissions of CO_2 as its main attraction.

The vast majority of fuel ethanol production in the United States [5.1 billion liters = 1.34 billion U.S. gallons in 1994 (44), equivalent to 59,000 barrels petroleum per day] is produced by fermentation from corn, using approximately 3.7% of the crop. Current corn kernel yields are about 7.5 t ha^{-1} year^{-1} (see Table 1) in the United States, and the US Department of Agriculture projects that this will double by the year 2030 (23).

Current US technology may be summarized (57):

$$\text{Corn} \xrightarrow{\text{(i)}} \text{Glucose} \xrightarrow{\text{(ii)}} \text{Broth} \xrightarrow{\text{(iii)}} \text{Ethanol}$$
$$\searrow \text{Animal Feed}$$
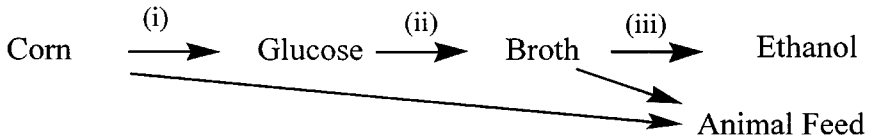
i. Dry or wet milling, followed by acid or enzymatic hydrolysis of the starch to sugars, principally glucose. Wet milling is more expensive, but provides a higher-value by-product. Enzymatic hydrolysis with fungal amylases appears to be more common than acid hydrolysis.

ii. Yeast fermentation in batch, although continuous processes have been developed.

iii. Distillation. Credits from the sale of yeast and corn by-products as animal feed are an important part of the economics.

As originally shown by Lavoisier (58), ethanol fermentation of one molecule of glucose (a six-carbon sugar) yields two molecules of ethanol and two molecules of CO_2. On a mass basis, this maximum yield is 0.511 kg ethanol kg^{-1} glucose. On an energy basis, this maximum yield retains 97% of the heat of combustion of glucose. In practice, typical efficiencies are slightly lower, e.g. 90% (0.46 kg ethanol kg^{-1} glucose) of the maximum yield, which amounts to an energy efficiency of 87%. Heat is also produced, and cooling is required in most fermentations.

A rule of thumb is 0.37 liters ethanol kg^{-1} dry corn (12%–15% moisture) (2.5 U.S. gallons bushel^{-1}), and about 2800 liters ha^{-1} (300 U.S. gallons acre^{-1}). Corn is currently relatively cheap, about half the price of oil on a weight basis. Nevertheless, the cost of corn is a major part of the cost of ethanol (some 40% after credits for by-products), and the cost of milling and fermentation are also major contributions to the cost of operations. Fermentation costs typically outweigh distillation by a factor of two. The current price of fuel ethanol is approximately

$0.30 liter^{-1} ($1.15 U.S. gallon^{-1}), and it would not be economically viable as a fuel additive in the United States without tax incentives; currently, these amount to $0.14 liter^{-1} ethanol, reducing the price to essentially that of regular gasoline. There is great interest in finding a cheaper feedstock for producing ethanol.

Cellulose is an obvious choice as a cheaper ethanol feedstock that would be available on a much larger scale than corn kernels (59). Unfortunately, it is more difficult to hydrolyze to its constituent sugars than is starch[1]. Furthermore, except in high-quality paper waste, cellulose is invariably associated with hemicellulose[2], a polymer containing high levels of xylose, which is not readily fermented to alcohol by traditional ethanolic yeasts. Ethanol has been made on a commercial scale from cellulose, usually after an acid hydrolysis at high temperature, with combustion of the hemicellulose components to provide process heat, but this is not currently practiced. There is much work in progress using fungal enzymes to depolymerize cellulose, either by adding isolated enzymes (61) or by inserting the cellulase genes into a fermenting yeast (62). A major limitation is that cellulases are markedly inhibited by their products (glucose and cellobiose). One way to overcome this limitation would be to develop a simultaneous depolymerization and fermentation system, so that glucose and cellobiose do not accumulate (63–66). Currently, this requires an expensive enzyme and a rather dilute fermentation liquor; genetic engineering should lower the cost of the enzyme, and may perhaps allow more concentrated fermentation broths, which would lower production and distillation costs (63, 67). It is noteworthy that Lynd (59) believes that optimizing processing, not biomass, offers by far the greatest opportunities for lowering the cost of fuel ethanol from biomass.

Maximal value from cellulose will be obtained by converting the hemicellulose as well as the cellulose to ethanol (68), and genetic engineering is being used to construct strains of bacteria capable of converting both hexoses (e.g. glucose) and pentoses (e.g. xylose) to ethanol (69). A quite different approach (70) would be to isomerize the xylose to fermentable xylulose over a zeolite catalyst.

Yet another alternative is to gasify the biomass and then ferment the synthesis gas to ethanol with *Clostridium ljundahlii* (71). None of these developments seems to be commercially practiced on any significant scale to date.

Even if the entire corn plant could be fermented to ethanol, however, it is unlikely that ethanol could compete on an equal economic footing with petroleum because of the substantial energy inputs in the farming process (72). Several groups have reported strain improvement of several tree species for maximizing biomass production that might be used for ethanol production (73–80). These groups envision coppice cropping of fast-growing trees as the feedstock, and using the lignin fraction of the wood to provide the energy for the fermentation of the cellulose and

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[1]Starch is a polymer of glucose linked primarily through α1,4-linkages; it is readily depolymerized by most organisms. Cellulose is also a polymer of glucose, but it is linked through β1,4-linkages; it is degraded by only a limited number of microorganisms (60).
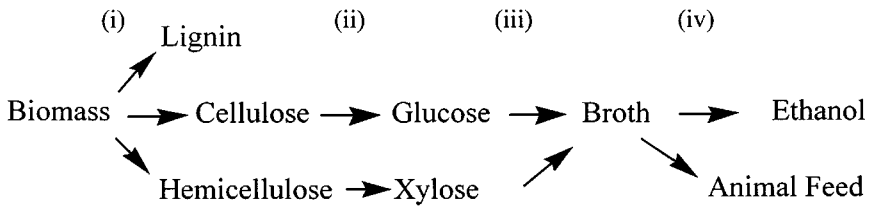
[2]Hemicelluloses are a heterogeneous group of carbohydrate polymers. They are typically branched and contain substantial amounts of pentose sugars.

hemicellulose fractions. Alternatively, fast-growing herbaceous crops and grasses might be used (73, 75, 81).

Biotechnology promises to have a dramatic impact on improving agriculture and forestry in the next few decades (32), and eventual yields of 9000 liters of ethanol hectare^{-1} year^{-1} (triple today's yield) on a sustained basis are envisioned. It may also be possible to grow high-yield energy crops on land that is unsuitable for current crops, but currently this is little more than an optimistic vision.

Current costs for ethanol from coppice biomass are claimed to be competitive with corn ethanol, with hopes to decrease the cost from \$0.32 to \$0.16 liter^{-1} (\$1.20 to \$0.60 U.S. gallon^{-1}) or even lower by implementing several incremental improvements (63, 77). Lynd (59) described cellulose ethanol from an advanced technology scenario at 13.3 cents liter^{-1} (50.3 cents U.S. gallon^{-1}).

Future ethanol production may look like this:

(i)   (ii)   (iii)   (iv)

Lignin

Biomass → Cellulose → Glucose → Broth → Ethanol

Hemicellulose → Xylose   Animal Feed

   i. The pretreatment stage would include heat, acid, or enzymatic hydrolysis. Some sources, such as recycled paper or paper mill effluent, may require almost no pretreatment.

  ii. Lignin[3] would be used for its fuel value, although potential higher value uses in wood products and plastics may become viable. Cellulose would probably be treated with fungal cellulases to yield glucose, although in situ production of cellulases is also a possibility. Hemicelluloses would be readily hydrolyzed to their constituent sugars, principally pentoses in the initial biomass treatment. The hexoses and pentoses may be separated at this stage.

 iii. The fermentation of the sugars to ethanol may either be by separate organisms on separate streams or by engineered organisms capable of handling both types of sugars simultaneously. The National Renewable Energy Laboratory envisions simultaneous depolymerization of cellulose and fermentation of the resulting sugars in one reactor.

 iv. Membrane technologies, such as pervaporation (membrane permeation combined with evaporation), may compete with distillation (82).

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[3]Lignin is the methoxylated phenylpropane structural polymer of plants. Very few organisms can degrade it, the principal degraders being the white-rot fungi. Even they only degrade it under certain conditions, and expend a lot of energy in the process. It is unlikely that lignin can be converted to ethanol with high yield.

An alternative fermentation approach is the ABE fermentation, named for the simultaneous production of acetone, butanol, and ethanol. This fermentation uses an anaerobic bacterium, *Clostridium acetobutylicum*, in place of the yeasts used in ethanol production; it is one of the oldest, and was until the early 1960s one of the most important, industrial fermentations (83). A related process was practiced on a large scale in Chula Vista, near San Diego, CA, during World War I, using kelp. The Hercules Powder Company built a plant for 800 workers working 24 hours per day, 365 days a year, designed to handle 1500 tonnes of kelp per day to produce acetone for cordite production; it was discontinued as soon as the war ended (84). With inexpensive petroleum, the ABE process is no longer economically viable. A major problem is that the products exert a profound feedback inhibition on the process, so it is run as a rather dilute fermentation. There is significant work aimed at overcoming this problem (see e.g. 85), but it is unlikely that this fermentation will regain its industrial importance, except perhaps as a niche disposal method for wastes such as whey (86).

3.3 Methanol

Methanol can be used to store chemical energy for use in fuel cells (as can ethanol), avoiding the storage and transportation problems inherent in the direct use of hydrogen in such systems. Methanol could be a potentially attractive transportation fuel for the future, provided effective methanol-powered fuel cells and fuel-cell/electric vehicles are developed.

The traditional name for methanol, wood alcohol, belies the product's early roots. Although most production is currently from fossil fuels, methanol can be produced from biomass by gasification, gas upgrading, and eventual synthesis over a copper-zinc oxide catalyst. Typical gasification plants produce approximately equal amounts of H_2 and CO so the water shift reaction, $CO + H_2O \rightarrow CO_2 + H_2$, is used to generate the necessary excess of H_2 to CO to drive the synthesis of methanol. Wyman et al (87) estimate that it will be hard for biomass to compete with natural gas as a feedstock for methanol synthesis without substantial tax incentives; current estimates are that biomass-derived methanol would be twice as expensive as that derived from natural gas. Nevertheless, it is said that biomass-derived methanol could be produced today at an estimated cost of $0.245 liter^{-1} ($0.93 U.S. gallon^{-1}) (88).

3.4 Plant Oils

Plant oils[4] have been exploited by humans for millennia for food and light. More recently, plant oils have also been considered as potential fuels, and as

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[4]Plant oils are almost invariably triacylglycerols, meaning a glycerol with three fatty acid esters. The fatty acids are typically 16–20 carbon atoms long, and odd-number acids are rare. Most plant fatty acids have one or more *cis* unsaturated bonds. Triacylglycerols are typically esterified to yield fatty acid esters and glycerol prior to use as a fuel.

the precursors for various chemical products that would presumably provide an alternative for petroleum-derived products. The yield of plant oils (in terms of energy content per hectare) is much lower than that of total biomass, but less manipulation is required to generate a useful transportation fuel. The major manipulation is transesterification with methanol, ethanol, or butanol to convert triglycerides to individual fatty acid esters and glycerol, followed by removal of the glycerol (89).

Total world production of edible plant oils was approximately 77 million tons in 1993 (90), 20%–30% of which was used for nonedible purposes. Different oils are grown in different parts of the world depending on climatic and political factors; soybean (*Glycine max*) oil is dominant today, accounting for 29% of world and 77% of U.S. edible consumption. The United States dominates world trade, with an average productivity of 2.25 t soybeans ha^{-1} and a total 1999 crop of 75 million tons. Soybeans yield approximately 23% of their dry weight as oil, and the yield of soybean oil is typically on the order of 570 liters ha^{-1} (cf Table 1). Rapeseed and other Brassica species yield 38%–44% oil, and yields of rapeseed oil are reported to be as high as 933 liters ha^{-1} by Peterson & Hustrulid (92). If we use current oil prices as a guide and assume that processing adds only 10% to the price, the current price would be $0.36 $liter^{-1}$ ($1.35 U.S. $gallon^{-1}$). The entire 1999 U.S. soybean crop would produce 15 billion liters of diesel substitute; current U.S. refinery output of diesel is approximately 100 billion liters $year^{-1}$ (1.7 million barrels day^{-1}). A recent analysis by the U.S. National Research Council (93) has recommended that the Department of Energy consider eliminating its program on biodiesel fuels because of a lack of foreseeable opportunities for reducing costs.

Marine algae also produce oils, although these are not yet commercially exploited. As discussed above, there are estimates that total microalgal productivity of biomass could be as high as 81 dry-t ha^{-1} $year^{-1}$ (34) if saturating levels of CO_2 were provided, perhaps from power station flue gases (94, 95). If 50% of this were oil, a not unreasonable goal, this would be the equivalent of more than 45,000 liters ha^{-1} $year^{-1}$ (100 barrels petroleum equivalent per acre per year). Current estimates are that liquid fuel could be produced from microalgae at a cost of $1.10 $liter^{-1}$ of petroleum equivalent ($177 per petroleum barrel equivalent) (63), with realistic hopes to reduce this to $0.31 $liter^{-1}$ of petroleum equivalent ($50 per barrel equivalent). Whereas this is very high for a transportation fuel, some specialty oils are this valuable, and these would be the first target for commercialization. Approximately one third of the current cost is for the CO_2 enrichment, and this cost could change dramatically if there were pressure to limit CO_2 releases.

A quite different approach is the catalytic upgrading of pyrolytic biomass oils (96). Yields of up to 75% oil have been obtained by low-pressure liquefaction of a variety of woody and nonwoody materials (97), although the resultant oils contain about 20% water and are poor fuels. Catalytic upgrading can generate a useful product (97), but little work has been done on scale-up.

3.5   Methane

Anaerobic degradation of biomass is an important part of modern waste treatment, and it can be modulated so that the majority of the biomass is converted to CO_2 and CH_4, typically with a significant excess of methane (98). More than 85% of the potential oxidation energy of the organic substrates is retained in the "biogas." Although small digestors are being installed in large numbers in the developing world, current commercial use of such reactors is mainly restricted to waste treatment facilities in agricultural (e.g. 99) and municipal waste applications (e.g. 100) where their gas production is secondary to the need to treat high organic load waste streams. If biogas were produced on a large scale to avoid greenhouse gas emissions, leakage of methane would have to be minimized because methane is a substantially more potent greenhouse gas than CO_2 (101).

3.6   Hydrogen

Hydrogen is an excellent fuel for fuel cells and has some attractive features as a transportation fuel (102), provided problems, e.g. with distribution and storage, are resolved. Biomass is potentially a suitable feedstock for producing hydrogen, and Ishitani & Johansson (8) suggest that the transport fuel yield, measured in GJ ha^{-1} of energy crop, could be three times higher for hydrogen from thermochemical gasification of wood than for ethanol from corn. Nevertheless, there are no commercial plants operating, to our knowledge, and there is little information to assess the validity of these predictions. Nevertheless, it is an active area of research. Current developments include three thermochemical methods for producing hydrogen from biomass: gassification and water shift, perhaps with natural gas as a co-feed (103); fast pyrolysis coupled with steam reforming of the resulting oil (104, 105); and direct hydrothermolysis (106). More generic developments being pursued with current hydrogen production from fossil fuels, such as improved systems for purifying and storing hydrogen, will obviously help make biomass-derived hydrogen more competitive. In addition, as discussed in Section 2.5, hydrogen can be produced by photosynthetic organisms (38–40) and by fermentation (e.g. 42, 107).

4.   SYSTEMS FOR BIOMASS ENERGY

A system for providing biomass energy on a large scale would produce biomass, transport it to a conversion facility, convert it to a usable, modern energy product, and deliver the product to the consumer. This system can be characterized by its greenhouse gas emissions, its economic cost, its environmental impacts, its resource requirements, and its various effects on society, and it can be compared with alternate systems on these bases. Our focus is on its greenhouse gas emissions and hence on the net efficiency with which solar energy can be converted to modern transportation fuels. Section 6 provides detailed descriptions of two systems

currently in large-scale application, but it is useful to look first at some general systems considerations.

The production of biomass could begin from the infrastructure in place for the production of food and forestry products. For efficiency, it would be preferable for biomass to be grown close to conversion facilities. Economy of scale is expected for some biomass fuel systems (108). If the scale of biomass energy increased, one might expect the system for planting, irrigating, fertilizing, harvesting, storing, and transporting the biomass to depart in some aspects from that used for agriculture. Specific crops could be developed. Land poor for agriculture might be used, although the productivity of this land would probably not be as high as for good agricultural land. On the other hand, the additional production of biomass for fuel could augment the food production system and lead to a system that might be more economically robust.

Transporting biomass adds to both the cost and the full fuel-cycle emissions of a biomass energy system. In Sweden, for example, biomass used for cogeneration of electricity is transported an average of 230 km, which leads to an increase in cost of roughly 20% and the use of 4% of the primary energy equivalent of the biomass (in the form of fossil fuels) when truck transport is used; rail or boat transport can require a factor of two to five less energy (109). This distance is quite large and Wright et al (110) suggest that practical constraints will typically limit transport distances to 80 km or so for truck transport. The distance over which biomass must be transported to a conversion facility could be minimized if the conversion facilities were not overly large, and if they were local to where the biomass was produced. This has been considered in the design of advanced biomass systems (111).

It is often assumed that regrowth of the crop following harvesting of biomass will offset all of the carbon released from the harvesting and use of the biomass. This might be true if there was no loss of soil carbon and if the regrown biomass contained the same amount of carbon as the harvested biomass. This would not be true, for example, if a mature forest was harvested and replaced by a fast-growing, short-rotation forest (which usually will contain less carbon that a mature forest). It will also not be true if cropland is replaced by a fast-growing, short-rotation forest (which will usually contain more carbon than cropland). In any case, there will be a time interval between when biomass emissions are incurred and when CO_2 is taken up by growth (112). This interval may be a matter of months for annual crops, years for short-rotation woody crops, or decades if the biomass is from traditional harvesting of trees. The time interval between when the biomass energy is used, and the emissions and costs are incurred, and the time when CO_2 is taken up may be of economic importance (113). Depending on whether the biomass system relies on preexisting plants or an energy crop, the carbon cycle may be initiated with uptake or release of carbon. If the value of avoided CO_2 emissions is discounted with time, the value for avoiding CO_2 emissions in the future would be less than the value of emissions avoided now.

In current systems for the production of biomass fuels, some CO_2 emissions originate from the carbon contained in the biomass, and some from other sources of

energy used in the production process. Biomass energy systems in use today focus less on the reduction of CO_2 emissions than on economic and other environmental impacts; that is, existing systems have not been designed or optimized for the purpose of reducing CO_2 emissions. For example, the system for producing ethanol in the United States (see Section 6.2) leads to a full-fuel-cycle emission that is only slightly less than for gasoline (114). Some early studies (e.g. 115) had suggested that the ethanol-from-corn fuel cycle might actually discharge more CO_2 than the comparable gasoline-based fuel cycle, but the most recent studies demonstrate that increases in corn productivity and decreases in energy use at corn milling facilities assure a net decrease in CO_2 emissions (116). Analysis of full-fuel-cycle emissions from potential systems (8, 117) shows that much lower emissions are possible.

5.   RESOURCE REQUIREMENTS FOR BIOMASS ENERGY AS A PRIMARY ENERGY SOURCE

The use of biomass energy on a scale that avoids a significant fraction of anthropogenic CO_2 emissions from fossil fuels would require significant resources (G Berndes, C Azar, T Kaberger, D Abrahamson, submitted for publication; 119). Resource requirements would include the capital and labor to create energy plantations and biomass conversion facilities, the land (assuming marine-based systems are not developed) for energy plantations, infrastructure to serve the increased extent of agriculture that is implied, and infrastructure to transport raw biomass to conversion facilities and products to consumers. Resource requirements would need to be compared with those required to provide a comparable supply of energy from alternate energy systems. Energy plantations would compete with the land requirements for both food and fiber and for settlement for a growing population. Whereas it is difficult to understand the implications of the extensive additional use of land required to make biomass a larger source of energy, we can estimate the land area that would be required relative to current land uses.

Of the Earth's surface (51×10^9 ha), roughly 29% is covered by land (14.9×10^9 ha) and the remainder is covered by ocean. Humans have put about 4.9×10^9 ha into productive use and we classify that land under three categories: (*a*) pastures and rangeland, (*b*) crops, and (*c*) settled land. Roughly 67% of this developed land is devoted to pastures and rangeland, 29% is devoted to crops, and human settlements cover about 4% (about 0.2×10^9 ha) (120, 121). Of the remaining 10.3×10^9 ha, roughly 4.4×10^9 ha are rock, ice, tundra, or desert (122), and are not suitable for the production of biomass. An additional 2.4×10^9 ha of the land area is dry woods, mosaics, or taiga that are not suitable for high rates of production of biomass. The remaining 3.5×10^9 ha are potentially suitable for use in producing biomass, or for extending the areas used for food crops or grazing.

Land available for growth of biomass intended for the production of biofuels varies by region. Currently, the land area cultivated for food production is increasing in most developing regions, whereas some previously cultivated land is either

left fallow or has been abandoned and is becoming reforested in developed countries. In general, there is fallow or abandoned land available in many developed countries, including the United States. In rapidly developing countries, high productivity land is mostly either used for agriculture or covered by forests. Additional agricultural land is being added by removing existing forests. There is growing concern over the rate of tropical deforestation in Southeast Asia, South America, and Africa. Table 2 lists the current land areas categorized by region and land coverage. Additional high-productivity land for fuel crops would likely come first from fallow and abandoned land and then potentially from areas currently covered by tropical or temperate forests. Land currently existing as grasslands, or being used as pasture, would often require irrigation and/or the application of fertilizer to produce biomass at high rates.

In 1996, the global emission of carbon, in the form of CO_2, from the burning of fossil fuels was 6.5 GtC year^{-1} (6). This represents emissions from a total primary energy consumption of 320 EJ year^{-1} (3.2×10^{11} GJ year^{-1}) of fossil fuels (7). Biomass in the form of sugarcane stems was harvested in Brazil in 1996/1997 at a rate of 65 t ha^{-1}, corresponding to a primary energy of 343 GJ ha^{-1} year^{-1}; this sugarcane was used to produce ethanol at a rate of 5170 liters ha^{-1} year^{-1}, with an energy content of 114 GJ ha^{-1} year^{-1} (see Section 6.1). If all the aboveground biomass of the sugarcane was harvested, this would contain a primary energy of 932 GJ ha^{-1} year^{-1}. If biomass could be produced broadly at the rate of Brazilian sugarcane stem, and if its primary energy could be used as a direct substitute for that of fossil fuels, then 0.93×10^9 ha of land could substitute the full primary energy of fossil fuels. This is 67% of the area of land used to grow crops worldwide today (1.4×10^9 ha). If all the aboveground biomass were a direct substitute, this would reduce the land area to 35% of today's cropland. If, however, useful energy were produced at the current rate of Brazilian ethanol, then twice the global area of crops would be needed to directly substitute all fossil fuel use. Note that these estimates do not account for fossil energy that may be used to produce biofuels. The estimates also do not include that part of the 320 EJ of fossil-fuel use that is not delivered to final users but is used for the production and processing of the fossil fuels. For advanced energy systems these two considerations may approximately cancel each other out.

6.   EXPERIENCES WITH SPECIFIC BIOMASS ENERGY SYSTEMS

Biomass was the traditional energy source of mankind until the development of fossil fuels. Even in recent years, biomass still provides some 14% of the world's primary energy and is the major source of energy in many developing countries (123). Biomass is used not only for cooking and space heat but also to provide process heat and to cogenerate electricity as in the paper, pulp, and timber industries. There has been large-scale contemporary production of ethanol in Brazil and the

TABLE 2 Estimated areas of land classified by land use and land coverage by region. Estimates based on a combination of land-use (133) and ecosystem (134) databases

Regions	Areas of land regions (G-ha = 10^7 km^2)							
	Tropical forest	Temperate forest	Boreal forest	Unusable land	Grassland	Cropland and settled land	Pastures and range	Total
Africa	0.26	0.22	0	0.71	0.76	0.20	0.79	2.95
Australia and New Zealand	0.003	0.14	0.001	0.12	0.01	0.05	0.45	0.78
Canada	0	0.06	0.35	0.43	0.18	0.05	0.03	1.11
Centrally planned Asia	0.05	0.16	0.04	0.27	0.08	0.13	0.44	1.18
Eastern Europe and Former Soviet Union	0	0.20	0.68	0.47	0.25	0.31	0.40	2.30
Japan	0	0.012	0.003	0.002	0.009	0.006	0.001	0.03
Latin America	0.60	0.10	0.002	0.18	0.35	0.19	0.56	1.99
Middle East	0	0.014	0	0.16	0.14	0.03	0.16	0.51
Noncommunist South East Asia	0.20	0.009	0.001	0.09	0.20	0.30	0.06	0.87
OECD-Western Europe	0.00	0.02	0.06	0.06	0.07	0.14	0.07	0.43
USA	0.0002	0.12	0.14	0.13	0.07	0.23	0.24	0.92
Total[a]	1.11	1.05	1.28	2.62	2.13	1.66	3.21	13.08

[a]Excludes Antarctica, Greenland, and inland waters.

United States for use as a transportation fuel. In this section we present quantitative estimates of the effectiveness of biomass fuel production in these two countries; results are summarized in Figure 3. In Section 6.3, we consider the land-use implications of extended production of biomass-derived transportation fuels in the United States using current technology.

6.1   Ethanol Production in Brazil from Sugarcane

Brazil has limited fossil fuel resources but significant hydroelectric power and expanses of forests and grasslands that could, in theory, be used for production of energy crops. Following the 1973 oil crisis, Brazil established the National Alcohol Program in 1975, with the intent of reducing Brazilian dependence on imported petroleum for gasoline-driven vehicles (56). By 1989, Brazil produced 12 billion liters of fuel ethanol per year, which was used to support 4.2 million cars running on hydrated ethanol and another 5 million cars running on gasohol (8, 124). The Brazilian alcohol program increased its market share until 1990. In 1985 automobiles that ran on pure ethanol represented 96% of new car sales. By 1996, the sale of pure-ethanol cars, however, had dropped to less than 1% of total car sales (54, 55). The supported price differential between ethanol and gasoline had been allowed to erode, and in 1990, the government adopted a policy of promoting small, inexpensive "popular cars," which could not be easily adapted to use pure alcohol.

In 1996/1997 Brazil used 4.2×10^6 ha of land to grow sugarcane, 1.51×10^6 ha for sugar and 2.69×10^6 ha for use in making ethanol. The land used for ethanol production was 4.8% of the land devoted to primary food crops in Brazil or 0.4% of the total land area of the country (55). Moreira & Goldemberg (55) suggest that the competition for land among energy, food, and export crops was not significant.

Brazil's average production rate for sugarcane stems in 1996/1997 was 65 t ha^{-1} (55), corresponding to 19.5 dry-t ha^{-1} year^{-1} (cf Table 1). Cane stem typically makes up about 53% of the dry above-ground biomass (30). If we adopt a carbon mass fraction of 44% and a nominal energy content of 40 GJ tC^{-1}, then the production rate of chemical energy stored in the harvested cane stems is 343 GJ ha^{-1} year^{-1}. If we adopt a nominal value for incoming solar radiation in Brazil (24) of 220 W m^{-2} (69,400 GJ ha^{-1} year^{-1}), then the efficiency of above-ground biomass production from sunlight is 0.93%, and the efficiency of cane stem production from sunlight is 0.49% (=53% × 0.93%). This efficiency may be compared to the maximum theoretical efficiency of C$_4$ plants of 6.7% (see section 2.1).

Cane stems contain about 14% sugar on a wet mass basis, which is the fraction currently fermented. This corresponds to 47% on a dry mass basis (cf Table 1).

The production rate of ethanol by the fermentation of sugarcane in Brazil increased from 2633 liters ha^{-1} year^{-1} in 1979 to 5,170 liters ha^{-1} year^{-1} in 1996. For a nominal energy content of ethanol of 0.022 GJ liter^{-1}, this yield gives 114 GJ ha^{-1} year^{-1} of ethanol. Compared with the chemical energy stored in cane
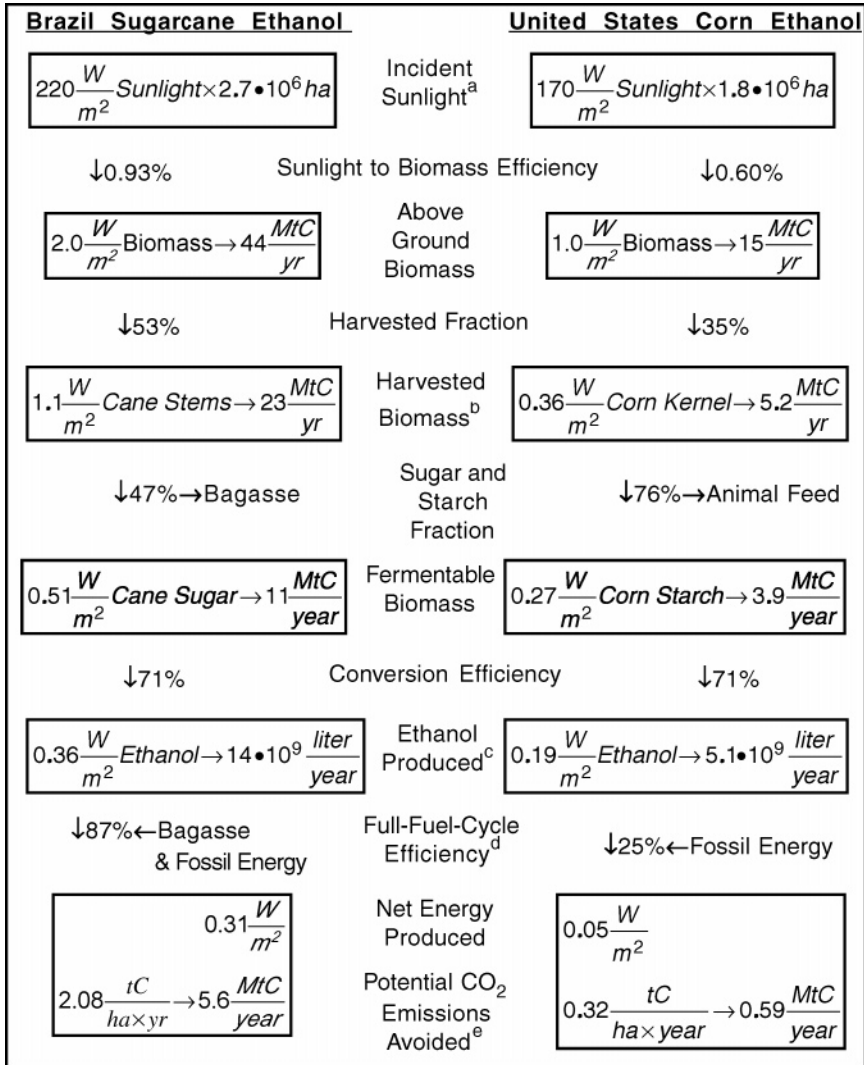
Figure 3 Comparison of ethanol production systems in Brazil (1996/1997) and the United States (1994).

[a]Incident sunlight is annual average over primary agricultural regions (24).

[b]Carbon content of harvested biomass taken to be 0.44 tC dry-t-biomass^{-1}. Energy in biomass taken to be 40 GJ tC^{-1}.

[c]Energy content of ethanol taken to be 0.022 GJ liter^{-1}.

[d]CO_2 emissions from additional energy supplied based on estimates for Brazil (55) and the United States (114, 128). Full-fuel-cycle efficiency defined as CO_2 emissions avoided relative to gasoline emissions substituted.

[e]Potential CO_2 emissions avoided assumes that the ethanol energy produced supplants gasoline energy with a carbon content of 0.021 tC GJ^{-1}, which includes 10% for production/refining of gasoline, times the full-fuel-cycle efficiency.

stem sugar, the efficiency of conversion to ethanol is 71%. Several factors contribute to the efficiency of conversion: e.g. the efficiency of fermentation and the fraction of extracted sugars. According to Wheals et al (27), the efficiency of fermentation is at 92% of the theoretical maximum of 0.51 kg ethanol kg^{-1} glucose, giving an energy efficiency of 89% for the fermentation step. As noted by Moreira & Goldemberg (55), the increase in the total reducible sugar yield was an important factor in the increase in ethanol yield from sugarcane. In addition, there is a significant side-stream of bagasse, the remaining cane fiber residue left after crushing cane to extract cane juice. Bagasse is widely used to produce process heat for sugar and ethanol production, and has potential as a fuel for electricity production (54).

The full-fuel-cycle emissions implied by the activities (see Figure 1) involved in the production of ethanol remain difficult to assess. In early assessments of the Brazilian program, an additional 22% of the energy produced was required for these activities (119, 125, 126). The key assumption is that all process heat and electricity are provided by bagasse. In some instances electricity is cogenerated for other uses. Fossil fuels consumed in 1996 to produce ethanol in Brazil were estimated to have resulted in CO_2 emissions of 0.82 MtC year^{-1} (55). The ethanol program is estimated to have led to additional CO_2 equivalent (based on a global warming potential with a 100-year time horizon) emissions of methane and nitrous oxide of 0.19 MtC equivalent year^{-1}. However, bagasse was estimated to have offset fuel oil consumption in the food and chemical industry by 0.87 MtC year^{-1}. If we assume that all ethanol produced in Brazil was used as a substitute for gasoline on an energy content basis, then CO_2 emissions from gasoline consumption (including 10% in excess of the gasoline carbon content to account for emissions in oil production/refining) would be reduced by 6.45 MtC year^{-1} ($=$5170 liters ethanol ha^{-1} year^{-1} $\times 2.7 \times 10^6$ ha $\times$ 0.021 tC GJ^{-1} gasoline $\times$ 0.022 GJ liter^{-1} ethanol). If emissions of non-CO_2 greenhouse gases are omitted, as well as the additional offsets from the use of bagasse, then the fossil fuel emissions for the production of ethanol account for 13% of the ethanol's substituted gasoline consumption. Therefore, 87% of the substituted CO_2 emissions would be avoided; this is referred to as the full-fuel-cycle efficiency in Figure 3. Thus, the potential CO_2 emissions avoided is 5.6 MtC year^{-1}. On average, 33% ($=$47% $\times$ 71%) of the primary energy content of harvested cane remains in the produced ethanol. Accounting for the full-fuel-cycle fossil emissions reduces the estimate of avoided, or offset, fossil emissions to 29% ($=$33% $\times$ 87%) of the primary energy in the harvested cane.

No change in carbon stock resulting from land use or land use change is included in the carbon balance estimates of Brazilian ethanol production given in Figure 3. Changes in carbon stocks might be the result of change in soil carbon content with continued cultivation, or loss of preexisting carbon (from, e.g. deforestation) of the sites where sugarcane is grown. Changes in carbon stocks at other locations may be also be a consequence of removing the land where sugarcane (for ethanol) is grown from alternative uses. Continued production of sugarcane over the past 25 years with increasing yields has quelled some early concerns that the ethanol

program would lead to soil degradation, which may be associated with loss of soil carbon (55). The net effect of sugarcane production on past and present land use change is complex and remains unclear.

6.2   Ethanol Production from Corn in the United States

The average U.S. corn kernel yield for the period around 1990 was 7.5 t ha^{-1} year^{-1} (23) (see Table 1). The harvested corn kernels make up approximately 35% of the dry mass of the above-ground corn plant (127). If we adopt a nominal value for incoming solar radiation in the Midwestern United States of 170 W m^{-2} (53,600 GJ ha^{-1} year^{-1}), then the efficiency of above-ground biomass production from sunlight is 0.60%, and the efficiency of corn kernel production from sunlight is 0.21% ($= 35\% \times 0.60\%$). This efficiency is compared to the maximum theoretical efficiency of C_4 plants of 6.7%.

Starch in the corn kernel, 76% of the dry mass (see Table 1), makes up the fraction that is currently fermented. On average, 1 kg of corn will yield 0.294 kg of ethanol (114). This gives a conversion efficiency (on an energy basis) of harvested starch to ethanol of 71%, similar to the cane ethanol system. U.S. production— 5.1×10^9 liters in 1994 (44)—of corn ethanol determines the area of corn cropland needed to supply the process feedstock.

Protein, which makes up the second largest fraction of the corn kernel (see Table 1), is not fermented, and is used primarily for animal feed. This is a key difference between the U.S. corn ethanol system and the Brazilian cane ethanol system. First, because protein production is currently a constraint on the economic production of ethanol from corn, credits from the sale of this by-product as animal feed are important determinants of the cost of ethanol. The market for animal feed is finite and would be affected by a dramatic increase in supply. Second, the corn kernel does not present a biomass stream, like bagasse, that provides process energy, leading to a lower full-fuel-cycle efficiency than in the cane ethanol system. Corn stover could be collected from the fields to provide process energy, but this is not done now.

The full-fuel-cycle emissions of greenhouse gases are rather large for ethanol from corn because of the large energy demands for fertilizer and other agricultural activities and for milling and fermentation. Whereas early studies by Pimentel (14) and Ho (115) suggested that full-fuel-cycle emissions of CO_2 were larger than for gasoline, recent studies show that with increases in corn productivity and in the energy efficiency of farming, fertilizer production, and ethanol processing over recent decades, this has not been the case for some years (114, 116, 128). The full-fuel-cycle efficiency for ethanol depends very importantly on how one treats the credits for by-products, but analyses by Wang et al (116) and Marland & Turhollow (114) suggest that energy supplements on the order of 75% of output are required for the full fuel cycle, as currently operated in the United States. Therefore, the avoided CO_2 emissions would be 25% of the substituted CO_2 emissions. This estimate does not account for emissions of gases other than CO_2 that could affect

climate. On average, 54% ($=76\% \times 71\%$) of the primary energy content of harvested corn kernel remains in the produced ethanol. Accounting for the full-fuel-cycle fossil emissions reduces the estimate of avoided, or offset, fossil emissions to 14% ($=54\% \times 25\%$) of the primary energy in the harvested corn kernel.

6.3   Considerations of Biomass Fuels to Supply 10% of the U.S. Transportation Market and Offset 10% of Transport Sector CO_2

As an example of the scale of effort that would be required to substitute renewable biomass for fossil fuel in the transport sector, we consider the implications of replacing 10% of current U.S. consumption of both diesel and gasoline with biomass-derived fuels produced using current technology. The most promising options in the near term would be the use of soybean oil (or other plant oil) to replace diesel fuel and ethanol from corn to replace gasoline. For these fuel products we address two questions. First, what would it take to replace 10% of today's gasoline and diesel consumption with biofuels, using current agricultural practices and biofuel technologies? Second, what would it take to offset 10% of today's CO_2 emissions generated by gasoline consumption by replacing gasoline with biofuel systems—including the energy inputs associated with cultivating, harvesting, and processing biomass?

Diesel-Fuel-Substitute   In 1997, U.S. diesel use for transportation was 100×10^9 liters year^{-1} (129). As discussed in Section 3.4, the entire U.S. soybean crop (used primarily for food products) was equivalent to 15×10^9 liters year^{-1} of diesel substitute, and used approximately 24×10^6 ha. To produce 10% of the 1999 diesel consumption, without taking from current production for food, would require an additional 16×10^6 ha to grow soybeans. There are not enough data to allow reliable estimates of the input of fossil fuels in producing this crop, but it is likely to be large because yields are low. To offset 10% of today's CO_2 emissions generated by diesel consumption would undoubtedly require a substantially greater acreage.

Ethanol   In 1995, U.S. gasoline consumption for transportation was 460×10^9 liters year^{-1} (120×10^9 U.S. gallons year^{-1}) (129). As discussed in Section 3.2, the United States produces enough fuel ethanol from corn to replace about 0.8% of this gasoline on an energy basis (1.1% on volume basis) on 1% of total U.S. cropland. At this yield, enough ethanol to replace the energy content of 10% of the 1990 U.S. gasoline consumption could be produced on 12% of U.S. cropland. The current ethanol production system is estimated to avoid 25% of the CO_2 emissions of the substituted (gasoline) emissions when energy consumed to grow and process the corn is accounted (114, 128). To offset the CO_2 emissions that result from 10% of the 1995 U.S. gasoline consumption would, therefore, require four times the production of ethanol and would nominally require an area

equivalent to 48% of current U.S. cropland. Production at this level would require reappraisal of the production and markets for by-products.

As discussed in Section 3.2, current research is aimed at improving ethanol productivity per acre by using a larger fraction of the total net primary productivity, i.e. by using cellulose in addition to or in place of starch. Success in this endeavor would require less land and would allow alternative energy crops that might not require such significant energy inputs to grow and harvest. In addition, the current system of ethanol (and soy oil) production is not optimized to reduce CO_2 emissions; modifications of this system (cf 117) could decrease the amount of energy consumed to produce ethanol.

Using current technologies to replace 10% of U.S. gasoline supply with ethanol or 10% of diesel supply with diesel-fuel-substitute would require large areas of land for crop production. To offset 10% of current CO_2 emissions from the transportation sector with current technologies would require very much larger land areas (four times as much). If land is the primary resource limitation and the goal is to offset CO_2 emissions, then the extent to which emissions can be offset with current biofuel technologies will be limited. As seen in Figure 3, the effective offset from the corn to ethanol process amounts to about 0.32 tC ha^{-1} year^{-1}. Production of ethanol is a more effective option than production of diesel-fuel-substitute because the rate of production of fuel per unit area is higher for ethanol (approximately 300 U.S. gallons per acre) than for diesel-fuel-substitute (60 U.S. gallons per acre).

Figure 4 illustrates the extent of land that would be required to produce energy in the form of corn-ethanol (*solid line*) and to offset CO_2 emissions from liquid fuels in the United States by producing even more ethanol (*dashed line*). The figure compares these relations to a variety of measures of U.S. land area and energy consumption. In 1992, total U.S. cropland was approximately 186×10^6 ha (460 million acres), of which 138×10^6 ha (340 million acres) were actively farmed. Presumably, the best land was used, but this indicates that there is a substantial reserve of potentially usable arable land for biofuel crops. Recent analyses have suggested that 14×10^6 ha (34 million acres) could be available for energy crops in the United States by 2030 without displacing current crops (33, 73). These curves could be moved upward on the figure by technologies that increase NPP, permit the capture of larger portions of NPP, or allow more efficient conversion to ethanol; however, the extent of potential improvement is limited by basic biophysics and chemistry.

7.   LONG-TERM ECONOMIC, PUBLIC POLICY, AND TECHNOLOGICAL CONSIDERATIONS FOR BIOMASS ENERGY

Production and distribution of biomass energy on a large scale will require significant resources of land, labor, conversion facilities, and infrastructure. Over a short time horizon, current valuations of land, labor, and energy can be used to estimate
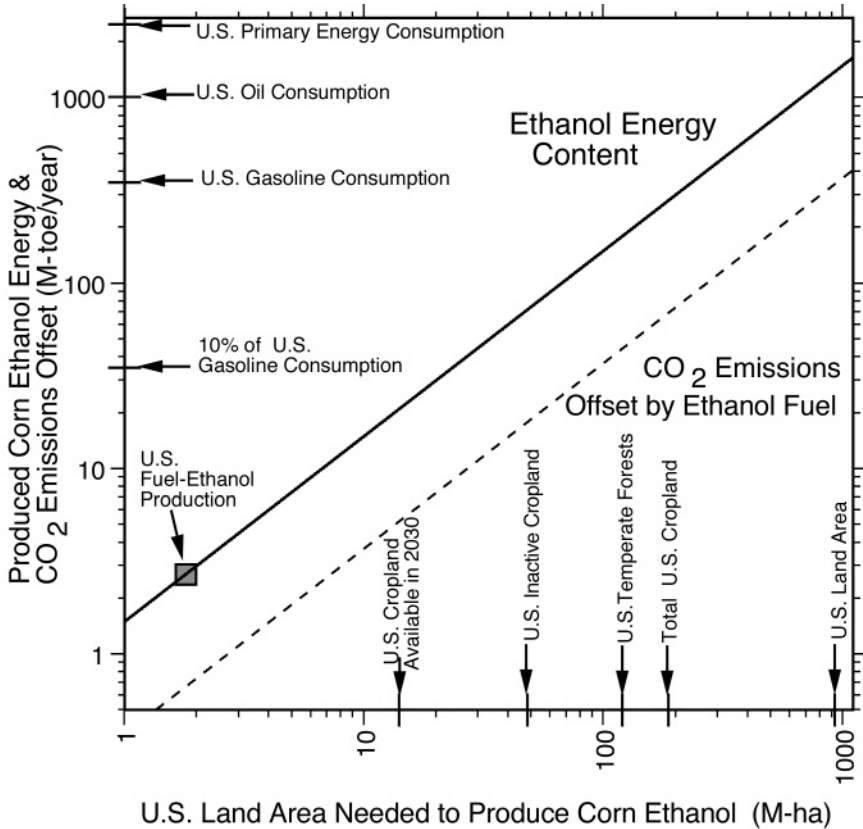
Figure 4   Comparison of the extent of land required to produce energy in the form of corn-ethanol (*solid line*) and to offset gasoline CO_2 emissions by producing even more ethanol (*dashed line*), assuming the current system processes and efficiencies for producing ethanol. U.S. land areas and energy consumption (1994) are marked along the axes. U.S. fuel-ethanol production in 1994 for all uses is marked by the *square symbol*. Note that the axes are logarithmic.

the near-term costs of biomass energy. Over longer time frames, current valuations may not reflect the future costs. In this section we note economic, regulatory, and technological factors that may influence the extent to which biomass energy is used in the U.S. transportation sector in the future.

7.1   Economic Factors

The price of energy will be affected by the development of all options for energy supply and demand. To some extent, demand for energy is specific to the nature of the end use: e.g. electricity, transportation fuels, industrial process heat, and traditional uses of biomass for cooking and space heating. Although there is

competition among energy carriers, over the short term each of these demands is met by different forms of energy: e.g. oil for transportation fuels and coal, gas, nuclear, or hydro for electricity. Demand for each form of energy, and the technologies to supply and use it, will evolve. The demand for transportation fuels is dependent on the performance aspects of the fuels and their alternatives and on the infrastructure for delivery and the technology of end-use systems. Biomass fuels, such as ethanol, have both negative and positive characteristics compared with gasoline. Electricity plays a role in some transportation systems, and the development and widespread use of personal electric vehicles and/or fuel cells would have a significant effect on the economics of demand for transportation fuels.

The make-up of the energy supply system depends in part on the relative costs for the various forms of energy. Although there are significant, accessible reserves of fossil fuels for the foreseeable future, shortages of oil for use as a transportation fuel may at some point encourage utilization of other fossil fuel resources, such as the large resources of heavy hydrocarbons (e.g. tar sands) that could be used to a greater extent in the future than they are today, or the conversion of coal to liquid fuels. If society were to assign a cost to CO_2 emissions, this would affect the economics of every option for energy supply and use. Sought-after advances in converting cellulosic biomass to liquid fuels could reduce the cost of biomass fuels, and the use of hydrogen, methanol, or ethanol for transportation using fuel cells could further reduce the cost of biomass fuels for transportation relative to fossil fuels. Biomass may be more cost effective for small-scale generation (<20 MW) in remote locations or where local production results in lower transport costs.

7.2   Public Policy Factors

Government policy affects the system for energy supply and use, and plays a significant role in land use. Government policies that might affect the introduction of biomass-based fuels could be proposed to:

1. Overcome perceived market or technological barriers. This might occur through incentives or regulations to promote the development of fuel cell–powered cars or advanced biofuel systems.

2. Influence the security of energy supply. Diversification to include energy sources such as domestically produced biomass could be used to soften the impacts of instability of energy supplies. Domestic biofuels could also be a source of instability owing to fluctuations in harvests caused by weather or outbreaks of pests or disease.

3. Influence the security of food supply. Biomass energy could be used to maintain active agricultural land, i.e. for energy crops, and this land could be readily converted for food production.

4. Influence labor demographics. Large-scale biomass plantations would affect the number and location of jobs (G Berndes, C Azar, T Kaberger, D Abrahamson, submitted for publication; 119).

5. Influence the balance of trade. Domestically grown biomass energy could be used to avoid costs of energy imports. Widespread use of biofuels may lead to use of foreign supplies (from different countries than oil suppliers) that would also affect the balance of trade.

6. Avoid environmental impacts. Policies may be chosen to mitigate, for example, the potential impacts of climate change by limiting activities that lead to greenhouse gas emissions, or the potential impacts on biodiversity by limiting activities that result in expansion of land use.

Government involvement has been essential in the limited uses of biomass fuels in the transportation sector to date. Brazil's choice to use sugarcane to produce ethanol as a domestic transportation fuel has been linked to their trade imbalance and to the migration of Brazil's poor to urban areas. The United States' use of corn to make ethanol has been linked to support of the agricultural sector and to reducing emissions from vehicles. There are ongoing U.S. government–funded programs to overcome technological barriers on the development of improved renewable energy systems. Requirements for zero emission vehicles and oxygenated fuels could have the effect of overcoming traditional market barriers for electric vehicles. These and similar initiatives could have an effect on the development path for biomass transportation fuels.

However, just as public policies can promote the development of new options, they can also discourage them, either intentionally or unintentionally. Whereas government intervention to create subsidies, incentives, or controlled markets can stimulate technological development, the potential for policy reversals adds an element of financial risk. Policies in unrelated spheres can have unintended consequences. As an example, utility deregulation has altered the economic incentive for many forms of renewable electricity.

7.3 Advanced Technology for Renewable Biomass Fuels

Alternative strategies for the production of biomass fuels have been proposed as a means for reducing net greenhouse gas emissions to the atmosphere. Some of these have been reviewed in the Second Assessment Report of the Intergovernmental Panel on Climate Change (8). These strategies aim to address some of the shortcomings apparent in the ethanol programs in the United States and Brazil. Most notably, they seek to make a larger portion of the energy of incoming solar radiation available as useful energy. The challenges are to capture a larger fraction of the solar energy in usable plant materials, to increase the efficiency of conversion to modern fuels, and to increase end-use efficiency of these fuels.

The large-scale growth of either corn or sugarcane for energy would rely on high-productivity agricultural land. Current agricultural practices require pesticides and fertilizer. In most advanced biomass strategies, alternative crops are preferred. Foremost among these are woody crops and fast-growing herbaceous crops (8, 33). These high-cellulose energy crops might be grown on lands that are

not well suited for food crops. Furthermore, these crops generally contain a lower ratio of plant nutrients (e.g. nitrogen) to energy than do the nonwoody plants and would likely not require intensive inputs of fertilizer.

The low conversion efficiency of solar energy to usable energy in biomass fuels via sugarcane is due primarily to the low fraction of convertible sugars in the cane plant. Similarly, corn ethanol is produced by using only the starch in the corn kernels. A greater fraction of the plant material could be used if cellulose, or the entire pyrolyzable fraction of biomass, could be converted to a useful fuel (130). If so, then cellulose in woody crops could be converted to ethanol by enzymatic hydrolysis, or the entire pyrolyzable fraction to methanol or hydrogen by thermochemical conversion. This gives a factor of 2.3 to 2.8 increase in the fuel energy produced per hectare when compared with the current corn-ethanol experience in the United States (0.19 W m^{-2} given in Figure 3).

Full-fuel-cycle carbon dioxide emissions for potential systems, with biomass converted to ethanol using enzymatic hydrolysis, have been estimated (130) to be about 25% of those produced by using gasoline, i.e. a full-fuel-cycle efficiency of 75%. Increasing the usable fraction of biomass, and decreasing nutrient content both contribute to higher full-fuel-cycle efficiency of this potential system. This is in contrast to the Brazilian cane-ethanol system that has taken an alternative path: use of biomass (e.g. bagasse) to fuel the process has been estimated to give an even higher full-fuel-cycle efficiency (87%; see Figure 3).

Avoided CO_2 emissions by substitution of biomass-derived fuels for fuel cells is less well characterized because it depends on the full-fuel-cycle efficiency of potential systems of both the biomass-derived and fossil-derived, energy-carrying fuel. These efficiencies are expected to differ with the potential fuel (e.g. hydrogen, methanol, ethanol, or a liquid fuel more closely associated with petroleum), so the estimate of avoided CO_2 emissions would depend on the selection of the energy-carrying fuel. With the impending introduction of fuel cell–powered vehicles, the choices for energy-carrying fuels may become apparent.

Biomass fuels could meet a larger fraction of the total demand for transportation fuels from the same amount of land if they were used in higher-efficiency vehicles. Both hybrid and fuel cell–powered electric-drive vehicles are expected to have the potential for significant increases in vehicle energy efficiency (e.g. double). If, for example, vehicle efficiency doubled and miles driven remained constant, fuel-energy consumption would decrease by half. If biofuels were produced at a fixed rate, the fraction of fossil transportation fuel that would be substituted would double. Even so, the absolute quantity of transportation fuels that would be substituted by biofuels in this hypothetical case would be unchanged. Of course, worldwide use of transportation as well as vehicle efficiency have both increased in the past and are expected to increase in the future. Growth of transportation has outpaced gains in efficiency, leading to increasing fuel consumption. These trends and potentials are included in the development of future scenarios for transportation fuel use.

8. CONSIDERATIONS FOR LARGE-SCALE BIOMASS ENERGY USE IN 2030

Energy use in the future will depend on population growth, economic growth, the energy intensity of the economy, technology development, and policy initiatives to support other objectives such as those discussed in section 7.2, including initiatives to limit emissions of greenhouse gases. Significant growth in populations and economies is expected in many developing countries. Increased consumption of energy will likely come primarily in those countries with a growing economic class capable of affording modern forms of energy and may not parallel rates of total population growth. Estimates of global population in the year 2030, surveyed by Morita et al (131), range from 6 to 12 billion, with a median value of 8.5 billion (compared with 5.3 billion in 1990). Fossil fuel CO_2 emissions could reach 9–19 GtC by 2030, up from the 1990 global estimate of 6 GtC. The question is the extent to which biomass fuels can contribute to a growing demand for energy and to a growing interest in reducing emissions of CO_2 to the atmosphere.

Current U.S. cropland is estimated to be approximately 186×10^6 ha, with about 14×10^6 ha projected to be available for energy crops in 2030 without displacing current crops (33, 73). Under scenarios that permit a large fraction of solar radiation to be converted to usable energy forms, this available land could produce 240×10^6 dry-t year^{-1} and 4.8 exajoules (EJ $= 10^{18}$ J) of biomass primary energy (at a heating value of roughly 20 GJ dry-t^{-1} of biomass), i.e. 1 W m^{-2}. Overend (132) writes similarly about a U.S. biomass potential, in 2030, of 5.3 EJ year^{-1} from a dedicated feedstock supply system on 20×10^6 h. Energy use in the United States (fossil fuel, nuclear, and hydroelectric) in 1998 was 90 EJ year^{-1} (7), with another 3 EJ from biomass (mostly as wood and wood waste in the pulp, paper, and paperboard industries. Worldwide, Johansson et al (29) estimate that there could be more than 350×10^6 h available for dedicated energy crops by 2025, with a potential energy yield of 80 EJ year^{-1}. This is 25% of the energy provided globally by fossil fuels in 1998, 320 EJ year^{-1} (7), and this would be 12.5% of fossil energy in 2025 if energy consumption doubled over this period.

With world energy consumption expected to roughly double by 2030 (9), the contribution of biomass energy (not including traditional uses of biomass for cooking and space heating) in some scenarios reaches 15% of the world's primary energy needs in 2030 (8–11). This fraction would, of course, be higher in some energy sectors and lower in others. This type of bioenergy-intensive scenario is conditional on high rates of bioenergy produced per unit land: on the order of 1 W m^{-2} of primary energy that can be produced and used with similar efficiency as fossil fuel primary energy.

The absolute magnitude of future biofuels production will depend on the resources and technology available and on the incentives for their application. The fractional contribution of biofuels to global energy supply will depend additionally

on the total demand for energy services. For biofuels to displace more than about 15% of fossil-fuel CO_2 emissions in 2030 will require a global economy that is more energy-efficient than is projected in most scenarios, one that has a lower total demand for carbon-based fuels.

9. CONCLUDING DISCUSSION

Biomass energy takes many forms. Whereas biomass today contributes about 14% of the global primary energy supply, the widespread use of biomass energy for cooking and space heating is very inefficient and is not usually seen as consistent with higher standards of living. Biomass can also be used to provide modern energy carriers, liquid and gaseous fuels, and electricity. Biomass contributes over 10% of primary energy supply in countries such as Sweden and Austria. In the United States, biomass supplies about 4% of primary energy, mostly for industrial applications in the pulp and paper industries. There has been a recent expansion of using waste biomass for industrial electricity and/or process heat, and interest in co-firing of coal-fired power plants to produce electricity or heat. Near-term use of biomass energy will likely focus on these approaches and the use of waste materials as the primary fuel. The expansion of biomass energy to substitute larger quantities of fossil-fuel energy and offset fossil-fuel CO_2 emissions would require dedicated production of energy crops. The contribution of biomass energy to the transport sector is smaller, but it does rely on a dedicated energy crop (sugarcane). Current production of fuel ethanol from corn in the Unites States produces the fuel equivalent of 0.8% of U.S. gasoline consumption. We have focused on the physical characteristics of dedicated biomass energy and on the efficiencies in the chain of conversion of solar radiation to usable, modern, transportation fuels.

Sunlight is a diffuse energy source with an average power density at the surface of the Earth of 180 W m^{-2}. The maximum potential photosynthetic conversion of sunlight to chemical energy is about 6.7%, but only a fraction of this is realized. Globally, only 0.3% of the solar energy falling on land is stored in plant matter, and only a fraction of this can be harvested. This is in contrast to solar photovoltaic cells, which can convert sunlight to electricity with an efficiency of nominally 10%. Higher-than-average utilization of sunlight can be achieved by the growth and harvesting of highly productive plants. For example, sugarcane converts roughly 0.5% of incident sunlight into energy that can be harvested as stems (0.9% if all the above-ground cane plant is harvested). There is potential in broadening the types of plants (to include e.g. woody and herbaceous plants) that can grow at high rates in a variety of climates and on a variety of landscapes. There is not great potential for increasing the utilization of sunlight by land plants much beyond the very high rates seen in the fastest growing crops such as sugarcane or corn. This sets a limit on the utilization of sunlight to create biomass.

Biomass can be converted into a variety of energy products and chemicals. To supply energy to the transportation sector, biomass could be used to produce a

liquid fuel (with the likely candidate being ethanol) (93) or electricity (if there was a conversion to electric-powered vehicles). Methanol, ethanol, and hydrogen are candidates for use in advanced (fuel cell–powered) vehicles. Conversion of corn kernels or sugarcane stems (biomass high in sugar or starch) to ethanol retains roughly half of the energy of the harvested biomass largely because only the sugar and starch are fermented. There is potential in advanced technologies to increase the fraction of biomass that can be converted to alcohols by including the fermentation of cellulose. This would not only permit a larger fraction of the plant to be converted to a liquid fuel, but would allow the use of other woody and herbaceous crops. In addition, fermenting a larger fraction of the harvest would reduce the size of byproduct streams that might not otherwise find a market if the scale of biofuel production were increased.

Net emissions of CO_2 to the atmosphere from a biomass energy system include (*a*) changes in the carbon stocks in the plants and soils from conversion of land to biomass production, (*b*) sequestration of CO_2 during the growth of biomass, and (*c*) emissions from fossil fuels used for production and transportation of biomass, conversion to an energy product, distribution, and end use. The production of ethanol from corn in the United States today produces roughly 75% of the CO_2 emissions as does the direct use of gasoline. To use corn-ethanol, produced with current technology, to avoid one unit of CO_2 emissions from gasoline would thus require substituting four units of gasoline with corn-ethanol.

The extent to which biomass fuels can displace fossil fuels in the transport sector, and their associated emissions of CO_2, will be limited by the land area required to produce the fuels and the efficiencies by which solar radiation can be converted to usable fuels. Current technologies are based on processes that can use only a fraction of the growing plant, and require large inputs of fuel for production, conversion, and delivery. Using them, the displacement of CO_2 emissions from transportation fuels in the U.S. is unlikely to reach 10%. To exceed this value will require processes that can utilize a larger fraction of the energy stored in plant biomass, and that require less energy-input for production, conversion, and delivery of fuels. Vehicles that are more fuel-efficient would permit biofuels to contribute a larger fraction of the total fuel requirement from the same harvested area. With current technology there are greater opportunities for offsetting fossil-fuel CO_2 emissions with biomass-derived electricity or heat because it is possible to utilize all of the harvested biomass, and the biomass can be converted to electricity and/or heat with efficiencies approaching those for fossil fuels.

A challenge for providing transportation fuels is to be able to substitute a joule of primary energy in harvestable biomass for a joule of primary energy in fossil fuel, and to do this without significant fossil energy consumption. Currently, the Brazil cane-ethanol system captures 33% of the harvested primary energy in ethanol. The U.S. corn-ethanol system captures 54%. Taking into account the fossil fuel emissions of CO_2 incurred in producing the cane- or corn-ethanol lowers the offset emission to 29% and 14%, respectively. If joule per joule substitution can be achieved, dedicated biomass plantations may be able to displace some 15% of the

CO_2 emissions expected from all uses of fossil fuels globally in 2030. For biofuels to displace more than about 15% of fossil-fuel CO_2 emissions in 2030 will require a more rapid improvement in the energy efficiency of the global economy than is apparent from past trends in efficiency.

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