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Roles for Biomass Energy in Sustainable Development

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Abstract

Advanced technologies such as gasifier/gas turbine systems for electric power generation and fuel cells for transportation make it possible for biomass to provide a substantial share of world energy in the decades ahead, at competitive costs. While biomass energy industries are being launched today using biomass residues of agricultural and forest product industries, the largest potential supplies of biomass will come from plantations dedicated to biomass energy crops. In industrialized countries these plantations will be established primarily on surplus agricultural lands, providing a new source of livelihood for farmers and making it possible eventually to phase out agricultural subsidies. The most promising sites for biomass plantations in developing countries are degraded lands that can be revegetated. For developing countries, biomass energy offers an opportunity to promote rural development.

Biomass energy grown sustainably and used to displace fossil fuels can lead to major reductions in carbon dioxide emissions at zero incremental cost, as well as greatly reduced local air pollution through the use of advanced energy conversion and end-use technologies. The growing of biomass energy crops can be either detrimental or beneficial to the environment, depending on how it is done. Biomass energy systems offer much more flexibility to design plantations that are compatible with environmental goals than is possible with the growing of biomass for food and industrial fiber markets. There is time to develop and put into place environmental guidelines to ensure that the growing of biomass is carried out in environmentally desirable ways, before a biomass energy industry becomes well established.

Introduction

Biomass (plant matter) has been used as fuel for millennia. In the 18th and 19th centuries it was widely used in households, industry, and transportation. In the United States, as late as 1854, charcoal still accounted for nearly half of pig iron production, and throughout the antebellum period wood was the dominant fuel for both steamboats and railroads (Williams, 1989). Biomass dominated global energy consumption through the middle of the 19th century (Davis, 1990). Since then biomass has accounted for a diminishing share of world energy, as coal and later oil and natural gas accounted for most of the growth in global energy demand. Today biomass is not much used by industry, though it is still widely used for domestic applications in developing countries—especially in rural areas (Hall *et al.*, 1993). Still, biomass accounts for about 15% of global energy use, only slightly less than the share of global energy accounted for by natural gas (see Figure 1).

Although the trend has been away from biomass as an energy source, there are strong reasons for revisiting biomass energy:

- Dependence on gasoline and diesel for transport fuels has led to urban air pollution problems in many areas that cannot be solved simply by mandating further marginal reductions in tailpipe emissions. California has adopted a policy mandating the phased introduction of low- and zero-emission transport vehicle/fuel systems. Other jurisdictions are likely to pursue similar policies (Wald, 1992), and in fact 12 eastern U.S. states in 1994 collectively asked the U.S. Environmental Protection Agency to impose the California regulations on them (Wald, 1994). Some biomass-based transport energy options could effectively address this challenge (Johansson *et al.*, 1993; Williams, 1994).
- The prospect of declining future production of conventional oil in most regions outside the Middle East (Masters *et al.*, 1990) once more raises concerns about the security of oil supplies. Fluid fuels derived from biomass substituted for imported oil can help reduce energy security risks (Johansson *et al.*, 1993).
- Responding to concerns about global warming may require sharp reductions in the use of fossil fuels (IPCC, 1990). Biomass grown sustainably and used as a fossil fuel substitute will lead to no net buildup in atmospheric carbon dioxide, because the CO_2 released in combustion is compensated for by the CO_2 extracted from the atmosphere during photosynthesis.
- A major challenge facing developing countries is to find ways to promote rural industrialization and rural employment generation, to help curb unsustainable urban migration (Goldemberg *et al.*, 1988, 1987). Low-cost energy derived from biomass sources could support such activities (Johansson *et al.*, 1993).
- There are large amounts of deforested and otherwise degraded lands in tropical and subtropical regions in need of restoration (Grainger, 1988). Some of these lands could be restored by establishing biomass energy plantations on them. Part of the revenues from the sale of biomass produced on such lands could be used to help pay for these land restoration efforts (Hall *et al.*, 1993; Johansson *et al.*, 1993).
- In industrialized countries, efforts to provide food price and farmer income stability in the face of growing foodcrop productivities has led to a system of large-scale agricultural subsidies. Despite mounting economic pressures to reduce or eliminate such subsidies, so doing is difficult politically (OECD, 1992). However, converting excess agricultural lands to biomass production for energy

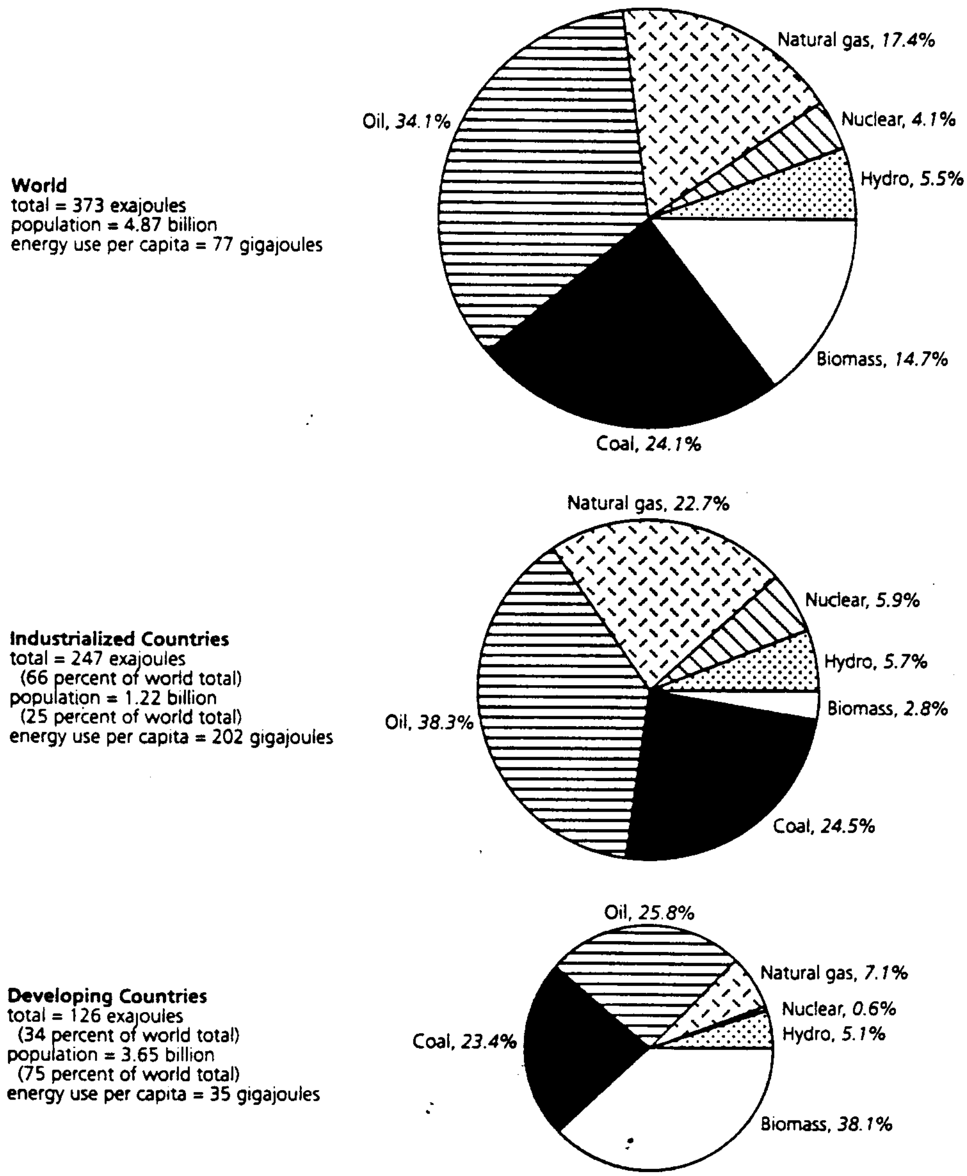


Figure 1. World primary energy consumption by energy source and by world region. Primary energy consumption is shown for the world (top), industrialized countries (middle), and developing countries (bottom) in 1985. Data from all energy sources except biomass are from Johansson *et al.* (1993). Biomass energy data are estimates based on surveys, from Hall *et al.* (1993).

The primary energy associated with electricity produced from nuclear and hydroelectric sources is assumed to be the equivalent amount of fuel required to produce that electricity, assuming the average heat rate (in MJ per kWh) for all fuel-fired power-generating units.

would provide both a new livelihood for farmers and an opportunity to phase out such subsidies (Hall *et al.*, 1993; Johansson *et al.*, 1993).

Such considerations, taken together with the good prospects for providing competitive energy supplies from biomass using modern energy conversion technologies, led a recent study exploring the prospects for renewable energy to project that biomass can have major roles as a renewable energy source (Johansson *et al.*, 1993). In a renewables-intensive global energy scenario constructed for that study it was estimated that renewable energy could provide about 45% of global primary energy requirements in 2025 and 57% in 2050, with biomass accounting for about 65% of total renewable energy in both years (see Figure 2). For the United States, the corresponding renewable energy shares of total primary energy were projected to be similar to the renewable shares at the global level, with biomass accounting for 55–60% of total renewable energy in this period (see Figure 3). In this scenario, biomass supplies are provided mainly by biomass residues of ongoing agricultural and forest product industry activities (e.g., sugar cane residues and mill and logging residues of the pulp and paper industry) and by feedstocks grown on plantations dedicated to the production of biomass for energy. The present analysis, is focused on plantation biomass, which accounts for about three-fifths of global biomass supplies in this scenario in the period 2025–50 (Johansson *et al.*, 1993).

The Challenges Posed by Biomass Energy

The notion of shifting back to biomass for energy flies in the face of conventional wisdom. Bringing about such a shift would require overcoming strong beliefs held by many people that biomass is inherently unpromising as an energy supply source. It is widely believed that:

- Biomass is an inconvenient energy carrier and thus unattractive for modern energy systems.
- The use of land to grow biomass for energy conflicts with land needs for food production.
- Large-scale production of biomass for energy would create environmental disasters.
- The energy balances associated with biomass production for energy are unfavorable.
- Biomass energy is inherently more costly than fossil fuel energy.
- Resource constraints will limit biomass to a minor role in a modern global energy system.

In what follows each of these concerns is dealt with in turn.

Attracting Consumer Interest by Modernizing Biomass Energy

Biomass is often called "the poor man's oil" (Goldemberg *et al.*, 1988, 1987). This characterization arises in part from the low bulk density of biomass fuels. Freshly

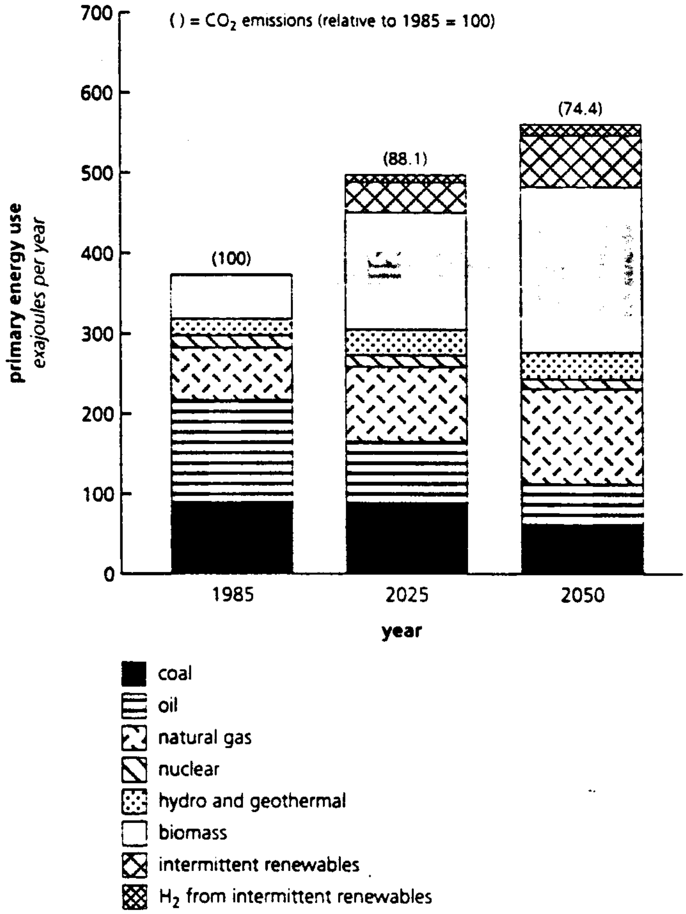


Figure 2. Global primary energy requirements for a renewables-intensive global energy scenario. This figure shows global primary energy requirements for the renewables-intensive global energy scenario developed in Johansson *et al.* (1993) in an exercise carried out to indicate the future prospects for renewable energy for each of 11 world regions. In developing this scenario, the high economic growth/high energy efficiency demand projections for solid, liquid, and gaseous fuels and electricity developed by the Response Strategies Working Group of the Intergovernmental Panel on Climate Change (Response Strategies Working Group of the Intergovernmental Panel on Climate Change, 1990) were adopted in Johansson *et al.* (1993) for each world region. For each region a mix of renewable and conventional energy supplies was constructed in Johansson *et al.* (1993) to match these demand levels, taking into account relative energy prices, regional endowments of conventional and renewable energy sources, and environmental constraints.

The primary energy associated with electricity produced from nuclear, hydroelectric, geothermal, photovoltaic, wind, and solar thermal-electric sources is assumed to be the equivalent amount of fuel required to produce that electricity, assuming the average heat rate (in MJ per kWh) for all fuel-fired power-generating units in a given year. This global average heat rate is 8.05 MJ per kWh in 2025 and 6.65 MJ per kWh in 2050.

For biomass-derived liquid and gaseous fuels the primary energy is the energy content of the biomass feedstocks delivered to the biomass energy conversion facilities.

Primary energy consumption in 1985 includes 50 EJ of noncommercial biomass energy (Hall *et al.*, 1993). It is assumed that there is no noncommercial energy use in 2025 and 2050.

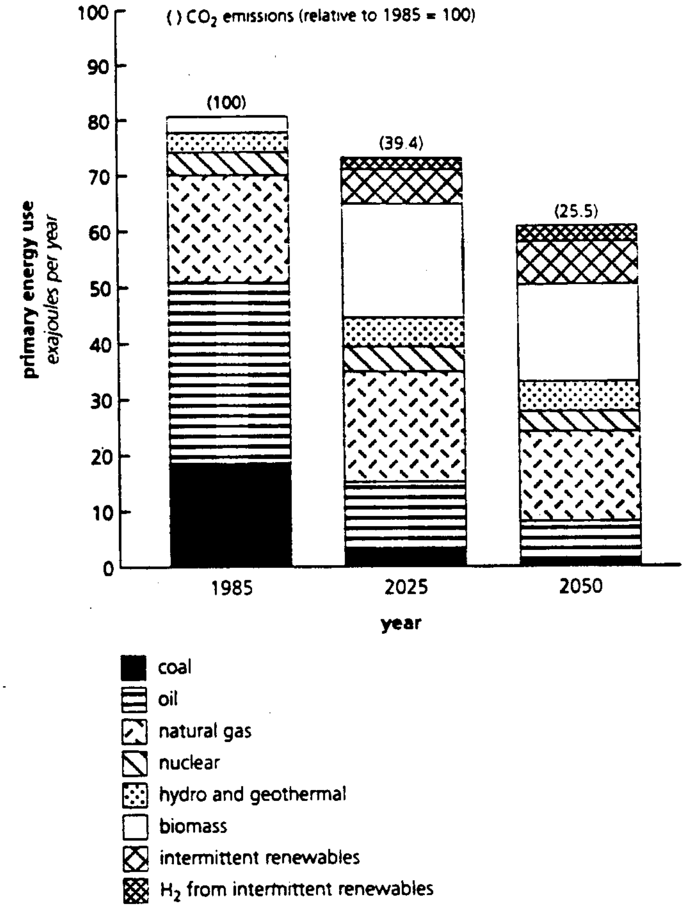


Figure 3. Primary energy requirements for the United States in a renewables-intensive global energy scenario. This figure shows primary energy requirements for the United States in the renewables-intensive global energy scenario developed in Johansson *et al.* (1993) in an exercise carried out to indicate the future prospects for renewable energy for each of 11 world regions, one of which is the United States. In developing this scenario, the high economic growth/high energy efficiency demand projections for solid, liquid, and gaseous fuels and electricity developed by the Response Strategies Working Group of the Intergovernmental Panel on Climate Change (1990) were adopted in Johansson *et al.* (1993). For the United States and other industrialized countries, this demand scenario involves a slow decline in primary energy demand as the economy expands, as a result of the emphasis given to improved energy efficiency. The mix of renewable and conventional energy supplies shown was constructed in Johansson *et al.* (1993) to match these demand levels, taking into account relative energy prices, endowments of conventional and renewable energy sources, and environmental constraints.

The primary energy associated with electricity produced from nuclear, hydroelectric, geothermal, photovoltaic, wind, and solar thermal-electric sources is assumed to be equivalent to the amount of fuel required to produce that electricity, assuming the average heat rate (in MJ per kWh) for all fuel-fired power-generating units in a given year. The U.S. average heat rate is 8.07 MJ per kWh in 2025 and 6.42 MJ per kWh in 2050.

For biomass-derived liquid and gaseous fuels the primary energy is the energy content of the biomass feedstocks delivered to the biomass energy conversion facilities.

cut wood typically has an energy density of about 10 GJ per tonne—compared with 25–30 GJ per tonne for various coals and more than 40 GJ per tonne for oil; it is thus both difficult and costly to transport biomass fuels long distances; in rural areas of developing countries women and children spend considerable time gathering fuelwood for cooking. Wood cookstoves also pollute—generating in rural kitchens of developing countries total suspended particulates, benzo-a-pyrenes, and other pollutants—often at levels far in excess of ambient air quality standards (Smith and Thorneloe, 1992).

As incomes rise, consumer preferences shift toward energy carriers of higher quality. The higher the quality of the fuel, the more convenient is its use and the less pollution is generated. This phenomenon is well-known in cooking fuels: charcoal is preferred to wood, kerosene is preferred to charcoal, and clean gaseous fuels such as liquid petroleum gas (LPG) are preferred to kerosene. This "energy ladder" is often invoked to show that consumers will shift away from biomass fuels as their incomes rise. For instance, data show that biomass accounts for 38% of energy use in developing countries (used mostly by poor people in rural areas), but just 3% of energy use in industrialized countries (see Figure 1).

However, with modern technologies, biomass can be converted into liquid or gaseous fuels or into electricity, in cost-effective ways. It is in these forms that biomass becomes an acceptable energy source at high-income levels.

Addressing the Food Vs. Fuel Controversy

The renewables-intensive global energy scenario developed in Johansson *et al.* (1993) calls for establishing worldwide some 400 million hectares of biomass plantations for energy by the second quarter of the 21st century—a land area that is not small compared with the nearly 1500 million hectares now in cropland (WRI, 1992). Because the world population is expected to nearly double by that time, the potential for conflict between biomass production for food and biomass production for energy warrants careful scrutiny. Because land is needed to grow food, but energy can be provided in many ways, food production should have priority. The key questions are: How much land is needed for food production? And how does this need compare with the arable land resource? In addressing these questions it is useful to consider the industrialized and developing country situations separately.

Industrialized Countries

Because their population growth is slow and food yields have been increasing, the amount of land needed for food production is declining in industrialized countries.

In the United States, more than one-fifth of total cropland, some 33 million hectares, was idled in 1990, either to keep food prices high or to control erosion. The U.S. Department of Agriculture forecasts that an area of over 50 million hectares may be idle by 2030 as a result of rising crop yields, despite an expected doubling of exports of corn, wheat, and soybeans (Soil Conservation Service, 1989). The urgency of addressing the challenge of excess agricultural lands was the major theme of the 1987 report of The New Farm and Forest Products Task Force to the Secretary of Agriculture:

> The productive capacity of U.S. agriculture is greatly underutilized. The country today has carryover stocks of between six months and one years production of major commodities, with productivity continuing to increase at a faster rate than demand. Estimates of land in excess of production needs to meet both domestic and export market demand range as high as 150 million acres [61 million hectares]—with about one-third of that already available from the Conservation Reserve Program. This represents an enormously wasted national asset which, if transformed into a more productive one through new products, would have a profoundly positive impact on the Nation's economy.

In the European Union more than 15 million hectares of land will have to be taken out of farming by the year 2000, if surpluses and subsidies associated with the Common Agricultural Policy are to be brought under control (Hummel, 1988). By 2015, according to a Dutch study, the land needed for food production in the community could be 50 to 100 million hectares less than at present (Netherlands Scientific Council for Government Policy, 1992). In the United States and the European Union together, therefore, 100 million hectares of farmland or more could be idle by the second decade of the next century, which is more than one-third of the total land dedicated to agricultural production today.

While the conversion of excess cropland in the industrialized countries to energy plantations presents an opportunity to make productive use of these lands, such a conversion cannot be easily accomplished under the present policies. In many countries farmers are deterred by a subsidy system that specifies what crops the farmer can produce in order to qualify for a subsidy; and energy crops are not allowed.

In 1991 this subsidy system transferred about $320 billion to farmers (170 billion in Western Europe, 80 billion in the United States, 60 billion in Japan, and 10 billion in Canada, in current U.S. dollars [OECD, 1992]). These subsidies, amounting to almost $400 per capita for the 800 million people living in the countries of the Organization of Economic Cooperation and Development, actually rose between 1987 and 1991, in spite of serious political efforts to reverse the tide (see Table 1). The calculation of these subsidies combines costs to consumers in the form of higher food prices (about $200 billion) and direct payments to farmers from taxpayer revenue (about $140 billion), and subtracts revenues from tariffs (about $20 billion). The $80 billion subsidy in the United States is about one-fifth of the total retail expenditure on energy sources in the United States (Energy Information Administration, 1991).

Gradual conversion of surplus cropland to profitable biomass energy production would make it possible to phase out many of these subsidies. As long as a system of subsidies continues, however, the bias against energy crops should be removed.

Table 1: *Subsidies to agricultural producers in OECD countries (current dollars)*

	Total Transfers ($ billions)		Per Capita Transfers ($)	
	1987	1991	1987	1991
Western Europe	139	166	390	440
EU (12 countries)[1]	119	142	370	410
Non-EU (5 countries)[2]	20	24	630	740
U.S.	81[3]	81	330	320
Japan	66	63	540	510
Canada	9	10	340	350
Australia and New Zealand	1	1	40	60
Total OECD	295	321	360	380

[1] European Union countries: Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, Netherlands, United Kingdom, Spain, Greece, and Portugal.
[2] Non-European Union countries: Austria, Finland, Norway, Sweden, and Switzerland.
[3] For comparison, U.S. retail expenditures on energy were $394 billion in 1987 (Energy Information Administration, 1991).

From OECD, 1992.

Developing Countries

For developing countries the situation is quite different. Because of expected population growth and rising incomes, it is likely that more land will be needed for food production. The Response Strategies Working Group of the Intergovernmental Panel on Climate Change has projected that the land in food production in developing countries will increase 50% by 2025 from the present level of about 700 million hectares (see Table 2) (IPCC, 1991). The demand can be compared to potential supply—that is, land physically capable of supporting economic crop production, within soil and water constraints. For 91 developing countries, potential cropland was estimated to be about 2000 million hectares—nearly three times present cropland (see Table 2) (FAO, 1991).

Looking to the year 2025 and assuming cropland requirements in developing countries increase 50% by then, there would still be a substantial surplus of potential cropland of nearly 1000 million hectares in these countries (see Table 2). There would be substantial regional differences, however, with major surpluses totaling more than 1100 million hectares in Latin America and Africa, and a 110 million hectare deficit in Asia. (China was not included in the U.N. Food and Agricultural Organization [FAO] analysis.) Thus it appears that substantial amounts of land suitable for energy plantations may be available in both Latin America and sub-Saharan Africa, even with major expansions of cropland to feed the growing population. But in Asia, with its high population density, conflicts with food production could become significant.

Table 2: *Present[1] and potential[2] cropland for 91 developing countries (million hectares)*

Region	Present Cropland	Potential Cropland: Low Rainfall	Uncertain Rainfall	Good Rainfall	Natural Flooded	Problem Land	Desert	Total
Central America	38	2.2	13	19	5.7	31	3.5	75
South America	142	26	38	150	106	493	2.8	815
Africa	179	73	97	149	71	358	3.8	753
Asia (excl. China)	348	60	67	67	81	118	20	413
Total	706	161	215	386	263	1000	30	2055

[1] From WRI, 1992.
[2] As estimated by the U.N. Food and Agriculture Organization (FAO) in 1990 (FAO, 1991). Potential cropland is defined by the FAO as all land that is physically capable of economic crop production, within soil and water constraints. It excludes land that is too steep or too dry or having unsuitable soils.

The extent of conflict with food production depends on future food crop productivities. Waggoner (1994) aruges that with feasible productivity gains a world population of 10 billion could be supported with no increase in cropland. Assessments are needed, country by country, to better understand the prospects for productivity gains and thereby the avoidance of food/fuel conflict.

Unfortunately, the FAO study does not clarify where new cropland would come from. To be sure, some forestlands are involved. Clearly, it would not be desirable to cut down virgin forests in favor of intensively managed biomass plantations. Cutting down virgin forests could be avoided, however, by targeting for biomass plantations lands that are deforested or otherwise degraded and that are suitable for reforestation. One estimate is that over 2000 million hectares of tropical lands have been degraded, of which about 600 million hectares are judged suitable for reforestation (see Table 3).

Outside of Asia the amount of degraded land suitable for reforestation (excluding degraded lands in the desertified drylands category), is substantial (see Table 3) —some 112 million hectares in Latin America and 62 million hectares in Africa. In Asia, such land areas are also large—some 115 million hectares; however, for Asia, country-by-country assessments are needed to determine the extent to which its degraded lands will be needed for food production or other purposes warranting higher priority than energy.

The main technical challenge of restoration is to find a sequence of plantings that can restore ground temperatures, organic and nutrient content, moisture levels, and other soil conditions to a point where crop yields are high and sustainable. Successful restoration strategies typically begin by establishing a hardy species with the aid of commercial fertilizers or local compost. Once erosion is stabilized and ground temperatures lowered, organic material can accumulate, microbes can

Table 3: *Geographical distribution of tropical degraded lands and potential areas for reforestation (million hectares)*

Region	Logged Forests	Forest Fallows	Deforested Watersheds	Desertified Drylands	Total
Latin America	44	85	27	162	318
Africa	39	59	3	741	842
Asia	54	59	56	748	917
Total	137	203	87	1650	2077
Area suitable for reforestation	–	203	87	331	621

From Grainger, 1988, 1990.

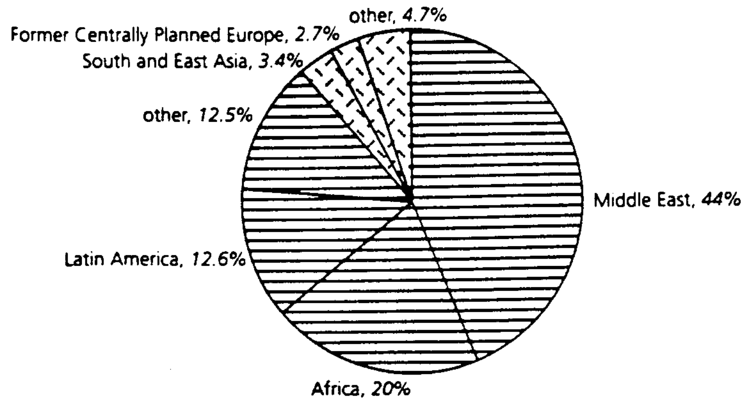
return, and moisture and nutrient properties can be steadily improved (OTA, 1992; Parham *et al.*, 1993).

If it is feasible to overcome this technical challenge and various other socioeconomic, political, and cultural challenges (Hall *et al.*, 1993), plantation biomass in developing regions could make substantial contributions to world energy without serious conflict with food production. In sub-Saharan Africa and Latin America, where potential land areas for plantations are especially large, biomass could be produced by the second quarter of the 21st century in quantities large enough to make these regions major exporters of biomass-derived liquid fuels, offering competition to oil exporters and bringing price stability to the global liquid fuels market (Johansson *et al.*, 1993). A possible interregional fuels trade scenario for 2050 is shown in Figure 4.

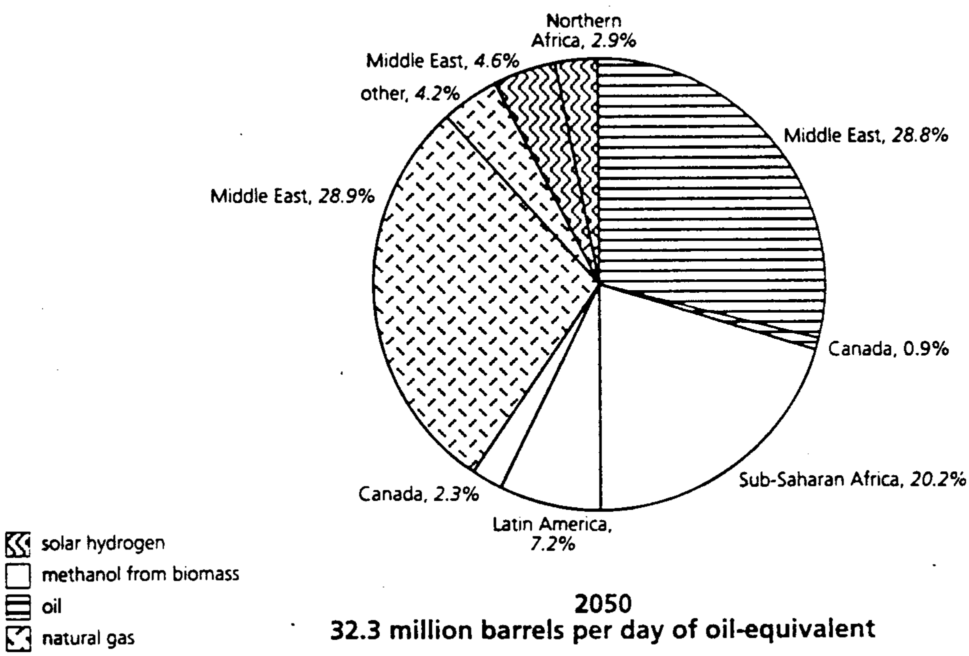
Converting such large areas of degraded lands to successful commercial plantations would be a formidable task. Research is needed to identify the most promising restoration techniques for all the different land types and conditions involved. Yet the fact that many of the successful plantations in developing countries have been established on degraded lands (Hall *et al.*, 1993) suggests that it may be feasible to deal with these challenges with adequate research and commitment. And interest in restoring tropical degraded lands is high, as indicated by the ambitious global net afforestation goal of 12 million hectares per year by the year 2000 set forth in the Noordwijk Declaration at the 1989 Ministerial Conference on Atmospheric and Climate Change in Noordwijk, The Netherlands (Ministerial Conference on Atmospheric Climatic Change, 1989).

Making Biomass Production for Energy Environmentally Attractive

Throughout the 19th and 20th centuries, there has been substantial deforestation worldwide, as a result of both land clearing for agriculture and nonsustainable mining of the forests for forest products. These cleared lands cannot support the diversity of species that once flourished there. Moreover, modern intensive agricultural management practices have created other serious environmental



1985
18.6 million barrels per day of oil-equivalent



2050
32.3 million barrels per day of oil-equivalent

Figure 4. Fuel exports by region for a renewables-intensive global energy scenario. The importance of world energy commerce for the renewables-intensive global energy scenario developed in Johansson *et al.* (1993) and for which global primary energy consumption is shown in Figure 2 is illustrated here. The figures show that by the middle of the next century there would be comparable exports of oil, natural gas, and biomass-derived methanol, as well as small exports of hydrogen derived from renewable sources. This diversified export mix is in sharp contrast to the situation today, where oil dominates international commerce in liquid and gaseous fuels.

Most methanol exports would originate in sub-Saharan Africa and in Latin America, where there are vast degraded areas suitable for revegetation that will not be needed for cropland (see Tables 2 and 3). Growing biomass on such lands as feedstocks for producing methanol (or other biomass fuels) would provide a powerful economic driver for restoring these lands.

problems, including loss of soil quality, erosion, and contamination of runoff with nitrates and other chemicals arising from the use of fertilizers, herbicides, and pesticides. A major concern is that such problems would be aggravated by a major shift to biomass energy.

There is no doubt that biomass can be grown for energy purposes in ways that are environmentally undesirable. However, it is also possible to improve the land environmentally through the production of biomass for energy. The environmental outcome depends sensitively on how and where the biomass is produced.

Consider first the challenge of sustaining the productivity of the land. Since the harvesting of biomass removes nutrients from the site, care must be taken to ensure that these nutrients are restored. This challenge can be dealt with for energy plantations more easily than for agriculture, largely because the choice among plants is more flexible, so that choices can be better targeted to environmental objectives. This is especially true for biomass conversion technologies that begin with thermochemical gasification (which will often be the preferred approach for providing modern energy carriers from biomass [Johansson *et al.*, 1993]).

With thermochemical gasification it is feasible to recover all mineral nutrients as ash at the biomass conversion facility and to return the ash to the plantation site for use as fertilizer. By contrast, fixed nitrogen is lost to the atmosphere at the conversion facility, but it can be replenished in several environmentally acceptable ways. First, when trees are the harvested crop, the leaves, twigs, and small branches, in which nutrients are concentrated, can be left at the site to reduce nutrient loss. (So doing also helps maintain soil quality and reduce erosion through the addition of organic matter to the soil.) Also, nitrogen-fixing species can be selected for the plantation or for interplanting with the primary plantation species to eliminate or reduce to low levels the need for artificial fertilizer inputs. The promise of intercropping strategies is suggested by 10-year trials in Hawaii, where yields of 25 dry tonnes per hectare per year were achieved without nitrogen fertilizer when Eucalyptus was interplanted with nitrogen-fixing Albizia (DeBell *et al.*, 1989).

Energy crops also offer flexibility in dealing with erosion and with chemical pollution from herbicide use. These problems occur mainly at the time of crop establishment. Accordingly, if the energy crop is an annual crop (e.g., sweet sorghum), the erosion and herbicide pollution problems would be similar to those for annual row-crop agriculture. The cultivation of such crops should be avoided on erodable lands. However, the choices for biomass energy crops also include fast-growing trees that are harvested only every 5 to 8 years and replanted perhaps every 15 to 24 years, and perennial grasses that are harvested annually but replanted perhaps only once in a decade. In both cases erosion would be sharply reduced, on average, as would the need for herbicides.

A major concern about agriculture is water pollution from nitrate runoff associated with the excessive use of nitrate fertilizers. Where it would not be possible to deal with this problem by planting nitrogen-fixing plantation species as an alternative to chemical fertilizers, runoff could be controlled by planting fast-growing trees in riparian zones (see Schnoor and Thomas, this volume). In the future it will also be possible to use "designer fertilizers" whose release is timed to match the temporal variations of the plant's demand for fertilizer (Linder, 1989; Kimmins, 1990).

Another concern is chemical pollution from the use of pesticides to control the plantation crop against attack by pests and pathogens. While plantations in the tropics and subtropics tend to be more affected by disease and pest epidemics than those in temperate regions, experience with plantations in these regions shows that careful selection of species and good plantation design and management can be helpful in controlling pests and diseases, rendering the use of chemical pesticides unnecessary in all but extraordinary circumstances. A good plantation design, for example, will include: (1) areas set aside for native flora and fauna to harbor natural predators for plantation pest control, and perhaps (2) blocks of crops characterized by different clones and/or species. If a pest attack breaks out on one block, a now common practice in well-managed plantations is to let the attack run its course and to let predators from the set-aside areas help halt the pest outbreak (Hall *et al.*, 1993).

Biomass plantations are often criticized because the range of biological species they support is much narrower than for natural forests. But if biomass plantations were established on degraded lands, the result could be a net improvement in ecological diversity. Similarly, if biomass energy crops were to replace monocultural food crops, in many cases the shift would be to a more complex ecosystem (Beyea *et al.*, 1992).

Preserving biodiversity will require careful land-use planning. At the plantation level, as already noted, establishing and maintaining natural reserves can be helpful in controlling crop pests while providing local ecological benefits. At the regional level, natural forest patches could be connected via a network of undisturbed corridors (riparian buffer zones, shelterbelts, and hedgerows between fields), thus enabling species to migrate from one habitat to another (Beyea *et al.*, 1992).

Achieving Favorable Energy Balances in Biomass Production for Energy

For biomass energy systems to be viable, the net energy balance must be favorable—i.e., the useful energy produced must be greater than the fossil fuel energy inputs required to provide the biomass energy. Concerns about net energy balances have been widely voiced in the case of fuel ethanol from maize (corn), which is produced in the United States under subsidy at a rate of 4 billion liters per year. In this case the net energy balance is often marginal, and in some instances, the fossil fuel inputs to the system are greater than the alcohol energy produced (Wyman *et al.*, 1993). Maize, however, is a feedstock intended primarily for use as food, not fuel, and its production system is more energy-intensive than most other biomass crops.

Many biomass energy systems have favorable energy balances. For example, in the production of fuel ethanol from sugar cane in Brazil (where production at a level of 12 billion liters per year provides nearly one-fifth of total transport fuel requirements) the energy content of the alcohol is about six times the fossil fuel inputs required to grow, harvest, and transport the cane and convert it to alcohol (Goldemberg *et al.*, 1993). The energy balances are also favorable for many energy plantation crops that might be grown in temperate climates. Table 4 shows that with present plantation technology, the energy contents of hybrid poplar, sorghum, and switchgrass harvested and hauled 40 km range from 11 to 16 times the fossil fuel energy needed to provide the biomass (Turhollow and Perlack, 1991). This harvested biomass could be used with near-term technology to produce methanol at an overall efficiency of nearly 60% (Katofsky, 1993), so the net energy balance would be 6 to 9 times the fossil fuel input. With improved yields in the future, these ratios are likely to be still higher (Turhollow and Perlack, 1991).

Achieving Attractive Economics by Modernizing Biomass Energy

The planting, cultivation, and harvesting of biomass is generally more labor-intensive and costly than recovering coal or other fossil fuels from the ground. Thus, per unit of contained energy, biomass tends to be the more costly, especially where there are abundant indigenous fossil fuel resources. Nonetheless, biomass energy

Table 4: *Energy balances for biomass production on plantations, 1990 technology*

	Hybrid Poplar	Sorghum	Switchgrass
Energy inputs (GJ/hectare)			
Establishment	0.14	1.3	0.39
Fertilizers	3.3	8.9	5.3
Herbicides	0.41	1.8	—
Equipment	0.17	—	—
Harvesting	7.3	3.7	5.5
Hauling[1]	2.4	3.8	2.8
Total	13.8	19.5	13.9
Energy output[2] (GJ/hectare)	224	233	158
Energy ratio[3]	16	12	11

[1] The energy required to transport the biomass 40 km to a biomass processing plant.
[2] Yields net of harvesting and storage losses are assumed to be 11.3 tonnes per hectare per year for hybrid poplar (with a heating value of 19.8 GJ/tonne), 13.3 tonnes per hectare per year for sorghum (heating value of 17.5 GJ/tonne), and 9.0 tonnes per hectare per year for switchgrass (heating value of 17.5 GJ/tonne).
[3] The energy ratio = energy output/energy input.

systems can be cost-competitive with fossil fuel energy systems. A more meaningful measure of economic performance is the cost of the energy services, taking into account conversion into electricity and gaseous or liquid fuels, and the systems in which the energy is used. On a cost-of-service basis the economic outlook for biomass can be favorable if modern conversion and end-use technologies are used. This is illustrated below first for electricity generated from biomass, and then for biomass-derived gaseous and liquid fuels for transportation.

Biomass Electricity

Today biomass, mainly in the form of industrial and agricultural residues, is used to generate electricity with conventional steam-turbine power-generators. These biomass power systems can be cost-competitive where low-cost biomass fuels are available, in spite of the fact that steam-turbine technologies are comparatively inefficient and capital-intensive at the small sizes required for biomass electricity production. The United States currently has more than 8000 megawatts of electric generating capacity fueled with such feedstocks, most of which was developed in the 1980s. (For comparison, total U.S. generating capacity is about 700,000 megawatts.) Biomass electricity generation using steam turbines will not expand much in the future, because unused supplies of low-cost biomass residues are rapidly becoming unavailable.

Biomass power generation involving the use of more costly but more abundant feedstocks could be made cost-competitive by adapting advanced-gasification technologies originally developed for coal for use with gas turbine-based power systems (Williams and Larson, 1993). Its very low sulfur content gives biomass a marked advantage over coal for power generation applications. With currently available sulfur removal technology, coal must be gasified in oxygen; the sulfur is removed from the product gas in a "scrubber" prior to combustion of the gas in the gas turbine. Since biomass has negligible sulfur, it can be gasified in air, thereby saving the substantial cost of a plant that separates oxygen from air, and expensive sulfur removal equipment is not needed. Biomass gasifier/gas turbine power systems with efficiencies of 40% or more will be demonstrated in the mid-1990s and will probably be commercially available by 2000. These systems offer high efficiencies and low unit capital costs for baseload power generation at relatively modest capacity (below 100 megawatts). Electricity from such systems will probably be able to compete with coal-fired electricity in many circumstances—even with relatively costly biomass feedstocks. By 2025, gas turbines may give way to even more efficient high-temperature fuel cells (Williams and Larson, 1993).

The electric power industry is beginning to appreciate the importance of biomass for power generation. In an assessment by the Electric Power Research Institute of the potential for biomass-based power generation, it is projected that biomass could be used to support 50,000 megawatts of electric capacity in the United States by 2010 and probably twice that amount by 2030 (Turnbull, 1993).

Transport Fuels from Biomass

Unlike the auspicious near-term outlook for biomass-derived electricity, very large increases in the world oil price are required before biomass-derived transport fuels could compete in cost with gasoline on a cost-per-unit-of-fuel-energy basis. Nevertheless, ongoing changes in the transport sector could permit biomass fuels to compete in providing transport services at world oil prices near the present low level. This prospect will be illustrated here for methanol and gaseous hydrogen fuels derived from biomass via thermochemical gasification.

Based on the use of gasification technology that could be commercialized by the turn of the century, it should be feasible to provide the consumer with either methanol or hydrogen derived from biomass at a cost that is only 40 to 50% more than the price of gasoline expected at that time. Moreover, these biomass-derived fuels are expected to cost no more than the same fuels derived from coal—even though the biomass feedstock would be more costly than coal. This surprising result is due in part to the fact that costly sulfur cleanup technology is not needed for biomass and in part to the fact that biomass is more reactive than coal, which makes it possible to gasify the biomass at a lower temperature. With either feedstock the product of gasification is a nitrogen-free synthesis gas (mainly carbon monoxide and hydrogen, plus some methane) that is subsequently processed to either methanol or hydrogen. In the case of coal, this synthesis gas is produced by gasification in oxygen; the needed high gasification temperatures are provided by partial oxidation of some of the coal in the gasifier; as for power generation, this entails the high cost of a plant to separate oxygen from air. In the case of biomass, gasification can be carried out in steam, with the needed heat provided by an external combustor; the lower gasification temperatures realizable with such "indirectly heated" gasifiers are adequate for biomass gasification, thereby obviating the need for the costly oxygen separation plant (Williams, 1994; Katofsky, 1993).

Synthetic fuels will be needed for transportation, in part to avoid overdependence on insecure sources of foreign oil. U.S. domestic crude oil production peaked in 1970; by 1993 production had fallen to 70% of the peak level; by 2030 production is expected to be less than 30% of the peak level (Department of Energy, 1991). Since biomass-derived synthetic fuels are expected to be no more costly than those derived from coal, they would be preferred in light of the environmental advantages.

A shift to synthetic fuels will probably be accelerated by air quality concerns posed by the use of the internal combustion engine in transportation. While it has dominated road transportation since the automobile was introduced, the long-term outlook for this engine is clouded by growing perceptions that air quality goals cannot be met simply by mandating further incremental reductions in tail-pipe emissions of new vehicles, and that a shift to very-low- or zero-emission vehicles is needed. Already the state of California has mandated that 10% of new cars purchased in 2003 must be zero-emission vehicles, and 12 eastern states have agreed to adopt the same requirement (Wald, 1994).

The California air-quality initiative has led to a substantial industrial effort to commercialize the battery-powered electric car. While the battery-powered electric car is a zero-emission vehicle, its potential is limited, without major advances in battery technology that make it feasible to overcome the long (several-hour) recharging time (Johansson *et al.*, 1993; Williams, 1994).

An alternative is the fuel-cell car operated on compressed hydrogen. As in the battery-powered electric car, electric motors provide the mechanical power that drives the wheels. But the electricity to run the motors is provided not by a battery but rather by a fuel cell that converts energy stored in compressed hydrogen gas canisters directly into electricity. Unlike the battery-powered electric car, the hydrogen fuel-cell car can be refueled in several minutes. Moreover, the life-cycle cost, i.e., the total cost of owning and operating a fuel-cell car (in cents per km) operated on hydrogen derived from biomass is likely to be less than for a battery-powered electric car (Johansson *et al.*, 1993; Williams, 1994; Katofsky, 1993). The life-cycle cost could also be less than for a car with an internal combustion engine of comparable performance even though the fuel is expected to be more expensive than gasoline, mainly because the fuel-cell car is expected to be three times as energy efficient and because it is expected to have lower maintenance costs.

A drawback of the hydrogen fuel-cell option is the requirement for an infrastructure for gaseous hydrogen under pressure. An alternative is to use methanol at atmospheric pressure as a hydrogen carrier: the methanol would react with steam in a "reformer" under the hood of the car, producing a mixture of carbon dioxide and hydrogen, thereby providing the hydrogen needed to operate the fuel cell. The main advantages of the methanol option are that it is easier to establish a distribution infrastructure for a liquid fuel than for pressurized hydrogen, and it is easier to store methanol onboard the car than pressurized hydrogen. The main drawbacks are that a methanol fuel cell vehicle would be more complicated, and it would not qualify as a zero-emission vehicle because of the small amounts of air pollutants generated by the reformer. Lifecycle costs for the methanol and hydrogen fuel cell vehicle options would be comparable (Williams, 1994; Katofsky, 1993).

Fuels derived from biomass are expected to become competitive on a lifecycle cost basis because both hydrogen and methanol can be readily used in technologically superior fuel-cell vehicles, while gasoline and other hydrocarbon fuels cannot—at least for first-generation fuel-cell vehicles.[1] Thus biomass-derived methanol could become a major energy carrier in international commerce in a world that is sensitive to environmental values. The world trade pattern for liquid fuels, shown in Figure 4 for a renewables-intensive global energy scenario (Johansson *et al.*, 1993), shows equal levels of trade for oil and biomass-derived methanol in the period 2025–50, based on an assumed indifference between these fuels.

[1]The most likely first candidate fuel cell for automotive propulsion is the proton-exchange-membrane fuel cell, which operates at about 100 °C. At such a low temperature it is practical to reform methanol on board the car, but not other fuels. In the future, if high-temperature fuel cells (operating at about 1000°C) become practical for vehicles, it may be feasible to reform a wide range of hydrocarbon or alcohol fuels under the hood of the car.

Creating Major Energy Roles for Biomass with Limited Land Resources

Because the photosynthetic process is a relatively inefficient way of converting solar energy into chemical-fuel energy, large land areas are required if biomass is to make major contributions to energy supply. For example, displacing fossil fuels in the United States with biomass grown on plantations at the average productivity of U.S. forests (4 dry tonnes per hectare per year) would require an area approximately equal to the total U.S. land area. This suggests that biomass can never become a significant energy source. While there is not enough suitable land to enable biomass to provide all energy needs, the role of biomass can nevertheless be substantial, if modern technologies are used for biomass production and conversion.

The land constraints on biomass production can be reduced in part by intensively managing the biomass plantations. With modern production techniques, biomass productivities far in excess of natural forest yields can be realized. A reasonable goal for the average harvestable yield on large-scale plantations in the United States is 15 dry tonnes per hectare per year (Hall *et al.*, 1993), corresponding to a photosynthetic efficiency of about 0.5%. Assuming that by 2030 the amount of land in the United States committed to biomass plantations is 30 million hectares—approximately the amount of excess cropland in the United States at present—biomass production would be about 9 EJ per year, more than 10% of current U.S. primary energy use (about 80 EJ per year).

The land constraints on biomass production can also be eased by exploiting for energy purposes urban wastes and residues of the agricultural and forest-product industries that can be recovered in environmentally acceptable ways. It has been estimated that such residues in the United States could amount to about 6 EJ per year (Beyea *et al.*, 1992).

The biomass energy potentially available from these two sources, some 15 EJ per year, could probably be produced in the United States in environmentally acceptable ways without confronting significant land-use constraints. This is equivalent to about 20% of current U.S. primary energy use, exclusive of biomass. It does not follow, however, that these potential biomass supplies would displace 20% of conventional U.S. energy. The extent to which conventional energy would be displaced depends sensitively on the conversion technologies deployed.

Consider, for example, the two energy activities often targeted for replacement by biomass energy: the generation of electricity from coal and the running of light-duty vehicles (automobiles and light trucks) on gasoline. In the United States these activities accounted in 1987 for some 30 EJ of primary energy and about one-half of total carbon dioxide emissions from fossil fuel burning. If these two activities (at 1987 activity levels) could be replaced by biomass grown renewably, the result would therefore be a 50% reduction in U.S. carbon dioxide emissions. Three examples of replacement technologies based on biomass are considered here. The overall results are displayed in Figure 5.

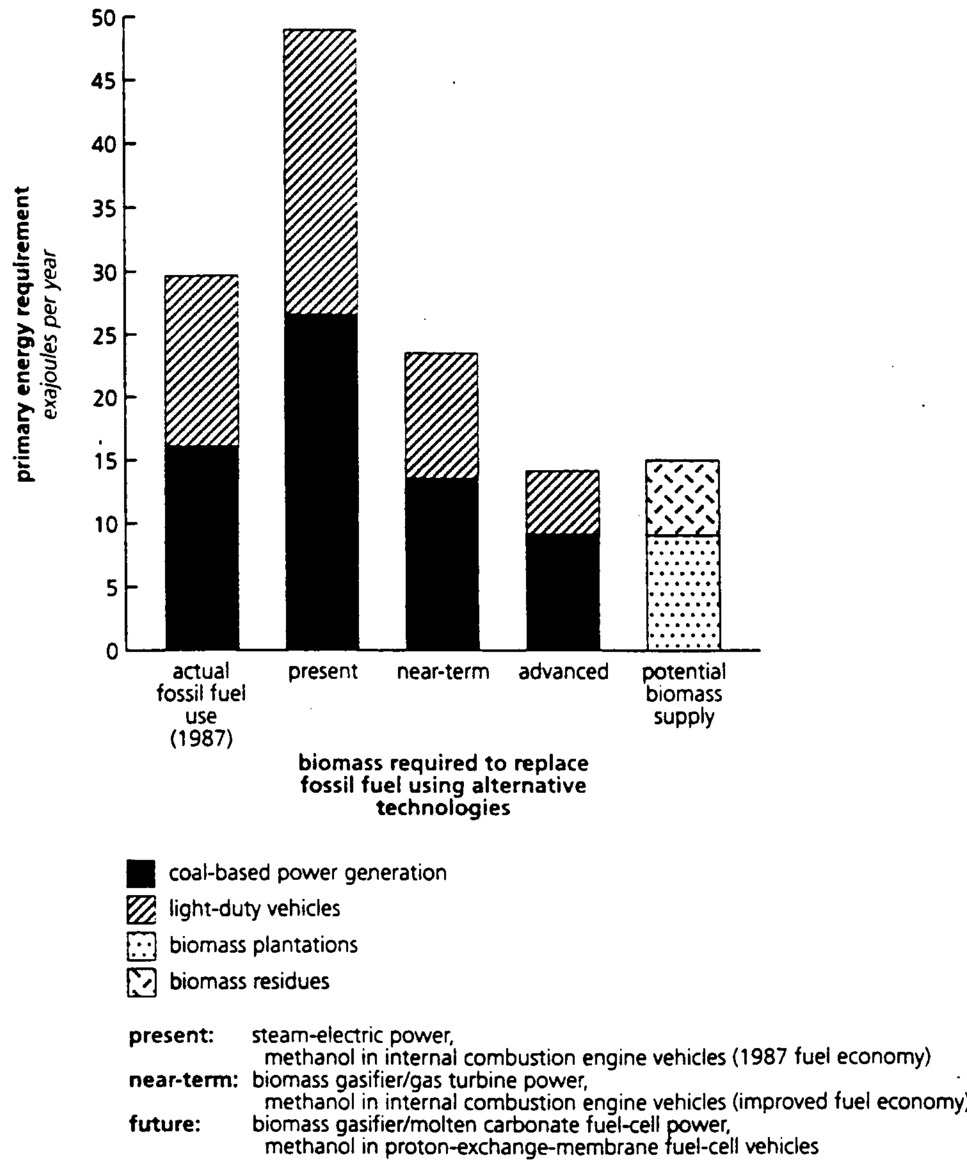


Figure 5. Energy for light-duty vehicles and power generation in the United States. Shown here are the biomass primary energy requirements for displacing all petroleum used by light-duty vehicles (automobiles and light trucks) and all coal-fired power generation in the United States, at the 1987 activity levels, with alternative biomass technologies, in relation to potential biomass supplies.

The bar on the left shows fuel actually consumed in 1987 by light-duty vehicles and by coal-fired power plants. The second bar shows the biomass primary energy requirements if light-duty vehicles and coal-fired power plants at 1987 activity levels were replaced by biomass energy systems that are commercially available today. The third bar shows biomass requirements if technologies likely to be available in the year 2000+ time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. The fourth bar shows the biomass requirements if technologies likely to be widely available in the 2020 time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. The bar on the

Suppose first that biomass were used with commercially available technologies: (1) replacing coal-based steam-electric power plants with biomass-based steam-electric power plants having a 20% average efficiency, and (2) replacing gasoline by methanol in internal-combustion-engine light-duty vehicles having 1987 average fuel economies, deriving the methanol from biomass (using commercially available technology designed to make methanol from coal but modified to accommodate biomass), and assuming no improvement in the fuel economy of the vehicles other than what would be inherent in a shift from gasoline to methanol. The amount of biomass needed annually for this conversion would be about 49 EJ per year, 60% more than the amount of fossil fuels now used for these purposes and more than three times the 15 EJ per year of biomass supplies estimated above to be potentially available.

Consider, instead, conversion technology likely to be available by the turn of the century. The first generation of biomass-integrated gasifier/gas turbine technology will probably be commercially available, making it possible to roughly double the efficiency of biomass power generation (Williams and Larson, 1993). In this time frame more energy-efficient biomass-to-methanol conversion technologies may also become available (Katofsky, 1993). Moreover, it will be feasible and cost-effective to introduce internal combustion engine vehicles operated on methanol having much higher fuel economies. Using these technologies the total biomass required to displace all coal-based power generation and all oil use by light-duty vehicles at 1987 activity levels would be reduced to 24 EJ per year.

During the second decade of next century, a third set of conversion technologies should be available, including energy-efficient fuel-cell technologies for both stationary electric power generation and motor vehicle applications. For stationary power applications one may anticipate 57% efficient biomass-integrated gasifier/fuel-cell systems employing molten-carbonate or solid-oxide fuel cells. For motor vehicle applications, one may see proton-exchange-membrane fuel-cell vehicles that are 2.5 times as energy-efficient as comparable gasoline-fired internal-combustion-engine vehicles. Using these technologies the total biomass required to displace all coal-based power generation and all oil use by light-duty vehicles at 1987 activity levels would be reduced to about 14 EJ per year, which is comparable to the above estimate of potential supplies from plantations and residues.

Thus with advanced technologies biomass can play major roles in the energy economy, despite the low efficiency of photosynthesis.

Figure 5 contd.
right shows potential biomass supplies from plantations on 30 million hectares of excess agricultural lands plus residues (urban refuse plus agricultural and forest product industry residues) that are recoverable under environmental constraints.

For details see Endnote for Figure 5, at the end of the chapter.

Conclusion

As a supply option for modern energy economies, biomass is unusual because its production and use would relate to a far wider range of human activities than any other energy source. This is in part because biomass energy is derived from photosynthesis, without which human life would not be possible. Biomass for energy could emerge as a human use of photosynthesis that is comparable in scale to that for agriculture or forestry.

If biomass energy systems are poorly managed, the benefits may not outweigh the social costs. But if biomass is well managed, it is likely that the major concerns people have about biomass energy could be addressed. Successfully developed, biomass energy could provide a broad range of environmental, social, and economic benefits. Worldwide, people could enjoy:

- competitively priced modern energy carriers for a substantial fraction of human energy needs, if advanced conversion and end-use technologies are used;
- the opportunity to reduce CO_2 emissions at zero incremental cost, through the displacement of fossil fuels;[2]
- fuels that are compatible with zero-emission or near-zero emission fuel-cell vehicles, for combating urban air pollution problems.

In addition, the worldwide development of a biofuels industry could provide interfuel competition, energy price stability, and increased energy security in the world fuels market. In developing countries, biomass energy plantations could provide a strong basis for rural development; an opportunity to pay for the restoration of many subtropical degraded lands through their conversion to biomass plantations for energy; and stimulation for economic development in sub-Saharan Africa and Latin America as they become large-scale biofuels exporters. In industrialized countries the development of biomass energy could benefit the agricultural sector by providing a new livelihood for farmers. It would also provide industrialized countries an opportunity to phase out agricultural subsidies eventually, thereby strengthening the economies of these countries while leveling the playing field in world trade for farmers in developing countries.

But these benefits cannot be realized without innovative public policies, coordinated internationally, designed to launch a new industry. An obvious first step would be to eliminate the various national policies biased against biomass energy systems, such as subsidies, tax incentives, and regulations that are not neutral across fuels. A coordinated international research and development program will

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[2] In addition, some carbon would be sequestered in the steady-state inventory of biomass plantations. Neglecting changes in soil carbon associated with establishing plantations and considering only the average inventory associated with biomass that will be harvested, the sequestering capacity would be about 9 billion tonnes of carbon (assuming an average rotation length of six years between cuts), corresponding to three years of buildup of carbon dioxide in the atmosphere.

also be necessary, with two parallel thrusts: (1) sustainable biomass production in a wide range of climates and soils, and (2) innovative, cost-effective energy conversion and end-use technologies. Agreement on environmental guidelines should be sought at an early stage, to give impetus to development and commercialization of options that are environmentally attractive, and to safeguard against undesirable and self-defeating approaches. Resources will have to be transferred from industrialized countries to developing countries to assure access to advanced biomass energy technologies in developing countries.

Five years ago, the required policy changes would have been deemed unrealistic, even unthinkable. But today this is no longer the case. A global consensus is emerging that the only acceptable development is sustainable development. This was the underlying theme of the United Nations Conference on Environment and Development in Rio de Janeiro, in June 1992. It is now realized that the only way to achieve sustainable development is to shift from one-dimensional policy-making to holistic approaches that deal with all direct and indirect impacts of a given economic activity, making concerted efforts to avoid adverse impacts before they occur.

Thus, though it is unfamiliar or at least not yet well understood by most people, biomass energy will receive focused attention in the forthcoming sustainable development debates—both because of potential disastrous consequences of ill-planned biomass energy developments and because of the enormous overall benefits in support of sustainable development goals that would arise from the proper development of biomass energy.

The timing of these debates could not be better for the biomass energy community. Because modernized biomass energy plays a negligible role in the world energy economy at present, the future shape of the biomass energy industry can be molded by the sustainable development debates, before the industry becomes well established.

It is a rare event in modern history that the big concerns about potential adverse impacts of technology are aired before the technology is implemented. And rarer still is the opportunity to address these concerns by timely changes of course.

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Endnote for Figure 5

The bar on the left represents fuel consumed in 1987 by light-duty vehicles and by coal-fired power plants. Automobiles and light trucks, with average fuel economies of 19.1 mpg and 12.9 mpg, respectively, consumed 103 billion gallons of gasoline. In 1987 coal-fired power plants, operated with an average efficiency of 32.9%, produced 1464 TWh of electricity.

The second bar shows the biomass primary energy requirements if light-duty vehicles and coal-fired power plants at 1987 activity levels were replaced by biomass energy systems that are commercially available today. With present biomass gasification technology (adapted directly from coal gasification) methanol can be produced from wood at 50% efficiency. Operated on methanol, cars and light trucks would have gasoline-equivalent fuel economies of 22.9 mpg and 15.5 mpg, respectively, some 20% higher than gasoline vehicles, because of the higher thermal efficiency of internal-combustion engines when operated on methanol (Wyman *et al.*, 1993). The net result is that the biomass feedstock requirements to support the 1987 level of light-duty vehicles would be $1/(0.5 \times 1.2) = 1.67$ times the amount of gasoline used by light-duty vehicles in 1987. The present average efficiency of biomass power plants operating in California is about 20%, so that the biomass plants would require $32.9/20 = 1.65$ times as much fuel to make electricity as the coal plants they would displace.

The third bar shows the biomass primary energy requirements if biomass technologies likely to be available in the year 2000+ time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. It is cost-effective to increase the average (on-the-road) fuel economy of new cars and light trucks to about 33.6 and 22.7 mpg (76% higher than in 1987), respectively, if operated on gasoline, and to 40.3 and 27.2 mpg of gasoline-equivalent energy (20% higher than on gasoline), respectively, if operated on methanol. A shift to such vehicles could be achieved over the next couple of decades. During this period it would be feasible to introduce methanol production technology involving indirect biomass gasification, for which the overall biomass-to-methanol conversion efficiency is 58% (Katofsky, 1993). With these technologies biomass fuel input requirements would be $(1/1.76)/(0.58 \times 1.2) = 0.82$ times as large as the petroleum required in 1987. If electricity were produced from biomass using biomass integrated gasifier/gas turbine technology that could be introduced commercially in this time frame, the efficiency of power generation would be 40%, nearly double that of existing biomass power plants, so that the biomass plants would require $32.9/40 = 0.82$ times as much fuel to make electricity as the coal plants they would displace.

The fourth bar shows the biomass primary energy requirements if biomass technologies likely to be available in the 2020 time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. By the end of the second decade of the 21st century, biomass-derived methanol could be routinely used in proton-exchange-membrane fuel-cell vehicles at gasoline-equivalent fuel economies that are 2.4 times the fuel economies of gasoline-powered internal-combustion-engine vehicles of comparable performance (Johansson *et al.*, 1993; Williams, 1993). With these technologies biomass fuel input requirements would be $(1/1.76)/(0.64 \times 2.4) = 0.408$ times as large as the petroleum required in 1987. Also, by that time, biomass integrated gasifier/fuel cell systems (using molten carbonate or solid oxide fuel cells) for stationary power generation could well be available with biomass-to-electricity conversion efficiencies of perhaps 57% (Williams and Larson, 1993), for which fuel requirements would be $32.9/57 = 0.577$ times coal requirements for power generation in 1987.

The fifth bar shows potential U.S. biomass supplies, consisting of (1) 9 EJ per year of plantation biomass grown on 30 million hectares of excess agricultural lands at an average productivity of 15 dry tonnes per hectare per year and a heating value of 20 GJ per dry tonne of biomass, plus (2) 6 EJ per year of those residues (urban refuse, agricultural residues, forest product industry residues) that are estimated to be recoverable under environmental constraints (Beyea *et al.*, 1992).