Biomass for Renewable Energy and Fuels

DONALD L. KLASS
Entech International, Inc.
Barrington, Illinois, United States

Glossary

barrels of oil equivalent (boe) The total energy content of a non-petroleum-based product or fuel in GJ divided by 5.904–6.115 GJ/boe.

biodiesel The methyl or ethyl esters of transesterified triglycerides (lipids, fats, cooking greases) from biomass.

biofuel A solid, gaseous, or liquid fuel produced from biomass.

biogas A medium-energy-content gaseous fuel, generally containing 40 to 80 volume percent methane, produced from biomass by methane fermentation (anaerobic digestion).

biomass All non-fossil-based living or dead organisms and organic materials that have an intrinsic chemical energy content.

biorefinery A processing plant for converting waste and virgin biomass feedstocks to energy, fuels, and other products.

gasohol A blend of 10 volume percent ethanol and 90 volume percent gasoline.

independent power producer (IPP) A nonutility generator of electricity, usually produced in a small capacity plant or industrial facility.

integrated biomass production conversion system (IBPCS) A system in which all operations concerned with the production of virgin biomass feedstocks and their conversion to energy, fuels, or chemicals are integrated.

landfill gas (LFG) A medium-energy-content fuel gas high in methane and carbon dioxide produced by landfills that contain municipal solid wastes and other waste biomass.

methyl *t*-butyl ether (MTBE) An organic compound used as an oxygenate and octane-enhancing additive in motor gasolines.

oxygenated gasoline Gasolines that contain soluble oxygen-containing organic compounds such as fuel ethanol and MTBE.

quad One quad is 10^{15} (1 quadrillion) Btu.

refuse-derived fuel (RDF) The combustible portion of municipal solid wastes.

tonnes of oil equivalent (toe) The total energy content of a non-petroleum-based product or fuel in GJ divided by 43.395–44.945 GJ/toe.

The world's energy markets rely heavily on the fossil fuels coal, petroleum crude oil, and natural gas as sources of thermal energy; gaseous, liquid, and solid fuels; and chemicals. Since millions of years are required to form fossil fuels in the earth, their reserves are finite and subject to depletion as they are consumed. The only natural, renewable carbon resource known that is large enough to be used as a substitute for fossil fuels is biomass. Included are all water- and land-based organisms, vegetation, and trees, or virgin biomass, and all dead and waste biomass such as municipal solid waste (MSW), biosolids (sewage) and animal wastes (manures) and residues, forestry and agricultural residues, and certain types of industrial wastes. Unlike fossil fuel deposits, biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource.

1. FUNDAMENTALS

1.1 The Concept

The capture of solar energy as fixed carbon in biomass via photosynthesis, during which carbon dioxide (CO_2) is converted to organic compounds, is the key initial step in the growth of virgin biomass and is depicted by the following equation:

$$CO_2 + H_2O + light + chlorophyll \rightarrow (CH_2O) + O_2. \quad (1)$$

Carbohydrate, represented by the building block (CH_2O), is the primary organic product. For each gram mole of carbon fixed, about 470 kJ (112 kcal) is absorbed.

The upper limit of the capture efficiency of the incident solar radiation in biomass has been estimated to range from about 8% to as high as 15%, but under most conditions in the field, it is generally less than 2% as shown in Table I. This table also lists the average annual yields on a dry basis and the average insolation that produced these yields for a few representative biomass species.

The global energy potential of virgin biomass is very large. It is estimated that the world's standing terrestrial biomass carbon (i.e., the renewable, above-ground biomass that could be harvested and used as an energy resource) is approximately 100 times the world's total annual energy consumption. The largest source of standing terrestrial biomass carbon is forest biomass, which contains about 80 to 90% of the total biomass carbon (Table II). Interestingly, marine biomass carbon is projected to be next after the forest biomass carbon in terms of net annual production, but is last in terms of availability because of its high turnover rates in an oceanic environment.

The main features of how biomass is used as a source of energy and fuels are schematically illustrated in Fig. 1. Conventionally, biomass is harvested for feed, food, fiber, and materials of construction or is left in the growth areas where natural decomposition occurs. The decomposing biomass or the waste products from the harvesting and processing of biomass, if disposed on or in land, can in theory be partially recovered after a long period of time as fossil fuels. This is indicated by the dashed lines in the figure. The energy content of biomass could be diverted instead to direct heating applications by collection and combustion. Alternatively, biomass and any wastes that result from its processing or consumption could be converted directly into synthetic organic fuels if suitable conversion processes were available. Another route to energy products is to grow certain species of biomass such as the rubber tree *(Hevea braziliensis)*, in which high-energy hydrocarbons are formed within the species by natural biochemical mechanisms, or the Chinese tallow tree *(Sapium sebiferum)*, which affords high-energy triglycerides in a similar manner. In these cases, biomass serves the dual role of a carbon-fixing apparatus and a continuous source of high-energy organic products without being consumed in the process. Other biomass species, such as the herbaceous guayule bush *(Parthenium argentatum)* and the gopher plant *(Euphorbia lathyris)*, produce hydrocarbons too, but must be harvested to recover them. Conceptually, Fig. 1 shows that there are several pathways by which energy products and synthetic fuels can be manufactured.

Another approach to the development of fixed carbon supplies from renewable carbon resources is to convert CO_2 outside the biomass species to synthetic fuels and organic intermediates. The ambient air, which contains about 360 ppm by volume of CO_2, the dissolved CO_2 and carbonates in the oceans, and the earth's large carbonate deposits, could serve as renewable carbon resources. But since CO_2 is the final oxidation state of fixed carbon, it contains no chemical energy. Energy must be supplied in a chemical reduction step. A convenient method of supplying the required energy and of simultaneously reducing the oxidation state is to reduce CO_2 with hydrogen. The end product, for example, can be methane (CH_4), the dominant component in natural gas and the simplest hydrocarbon known, or other organic compounds. With all components in the ideal gas state, the standard

$$CO_2 + 4H_2 \rightarrow CH_4 + H_2O \quad (2)$$

enthalpy of the process is exothermic by −165 EJ (−39.4 kcal) per gram mole of methane formed. Biomass can also serve as the original source of hydrogen via partial oxidation or steam reforming to yield an intermediate hydrogen-containing product gas. Hydrogen would then effectively act as an energy carrier from the biomass to CO_2 to yield a substitute or synthetic natural gas (SNG). The production of other synthetic organic fuels can be carried out in a similar manner. For example, synthesis gas (syngas) is a mixture of hydrogen and carbon oxides. It can be produced by biomass gasification processes for subsequent conversion to a wide range of chemicals and fuels as illustrated in Fig. 2. Other renewable sources of hydrogen can also be utilized. These include continuous water splitting by electrochemical, biochemical, thermochemical, microbial, photolytic, and biophotolytic processes.

The basic concept then of using biomass as a renewable energy resource consists of the capture of solar energy and carbon from ambient CO_2 in growing biomass, which is converted to other fuels (biofuels, synfuels, hydrogen) or is used directly as a

TABLE I

Examples of Biomass Productivity and Estimated Solar Energy Capture Efficiency

Location	Biomass community	Annual yield dry matter (t/ha-year)	Average insolation (W/m^2)	Solar energy capture efficiency (%)
Alabama	Johnsongrass	5.9	186	0.19
Sweden	Enthrophic lake angiosperm	7.2	106	0.38
Denmark	Phytoplankton	8.6	133	0.36
Minnesota	Willow and hybrid poplar	8–11	159	0.30–0.41
Mississippi	Water hyacinth	11.0–33.0	194	0.31–0.94
California	*Euphorbia lathyris*	16.3–19.3	212	0.45–0.54
Texas	Switchgrass	8–20	212	0.22–0.56
Alabama	Switchgrass	8.2	186	0.26
Texas	Sweet sorghum	22.2–40.0	239	0.55–0.99
Minnesota	Maize	24.0	169	0.79
New Zealand	Temperate grassland	29.1	159	1.02
West Indies	Tropical marine angiosperm	30.3	212	0.79
Nova Scotia	Sublittoral seaweed	32.1	133	1.34
Georgia	Subtropical saltmarsh	32.1	194	0.92
England	Coniferous forest, 0-21 years	34.1	106	1.79
Israel	Maize	34.1	239	0.79
New South Wales	Rice	35.0	186	1.04
Congo	Tree plantation	36.1	212	0.95
Holland	Maize, rye, two harvests	37.0	106	1.94
Marshall Islands	Green algae	39.0	212	1.02
Germany	Temperate reedswamp	46.0	133	1.92
Puerto Rico	*Panicum maximum*	48.9	212	1.28
California	Algae, sewage pond	49.3–74.2	218	1.26–1.89
Colombia	Pangola grass	50.2	186	1.50
West Indies	Tropical forest, mixed ages	59.0	212	1.55
Hawaii	Sugarcane	74.9	186	2.24
Puerto Rico	*Pennisetum purpurcum*	84.5	212	2.21
Java	Sugarcane	86.8	186	2.59
Puerto Rico	Napier grass	106	212	2.78
Thailand	Green algae	164	186	4.90

Note. Insolation capture efficiency calculated by author from dry matter yield data of Berguson, W., *et al*. (1990). "Energy from biomass and Wastes XIII" (Donald L. Klass, Ed.). Institute of Gas Technology, Chicago; Bransby, D. I., and Sladden, S. E. (1991). "Energy from Biomass and Wastes XV" (Donald L. Klass, Ed.). Institute of Gas Technology, Chicago; Burlew, J. S. (1953). "Algae Culture from Laboratory to Pilot Plant," Publication 600. Carnegie Institute of Washington, Washington, DC; Cooper, J. P. (1970). "Herb." *Abstr. m*, **40**, 1; Lipinsky, E. S. (1978). "Second Annual Fuels from Biomass Symposium" (W. W. Shuster, Ed.), p. 109. Rensselaer Polytechnic Institute, Troy, New York; Loomis, R. S., and Williams, W. A. (1963). *Crop. Sci.* **3**, 63; Loomis, R. S., Williams, W. A., and Hall, A. E. (1971). *Ann. Rev. Plant Physiol.* **22**, 431; Rodin, I. E., and Brazilevich, N. I. (1967). "Production and Mineral Cycling in Terrestrial Vegetation." Oliver & Boyd, Edinburgh, Scotland; Sachs, R. M., *et al.* (1981). *Calif. Agric.* **29**, July/August; Sanderson, M. A., *et al.* (1995). "Second Biomass Conference of the Americas," pp. 253–260. National Renewable Energy Laboratory, Golden, CO; Schneider, T. R. (1973). *Energy Convers.* 13, 77; and Westlake, D. F. (1963). *Biol. Rev.* **38**, 385.

source of thermal energy or is converted to chemicals or chemical intermediates.

The idea of using renewable biomass as a substitute for fossil fuels is not new. In the mid-1800s, biomass, principally woody biomass, supplied over 90% of U.S. energy and fuel needs, after which biomass energy usage began to decrease as fossil fuels became the preferred energy resources. Since the First Oil Shock of 1973–1974, the commercial utilization of biomass energy and fuels has increased slowly but steadily. The contribution of biomass energy to U.S. energy consumption in the late 1970s was more than

TABLE II

Estimated Distribution of World's Biomass Carbon

	Forests	Savanna and grasslands	Swamp and marsh	Remaining terrestrial	Marine
Area (10^6 km^2)	48.5	24.0	2.0	74.5	361
Percentage	9.5	4.7	0.4	14.6	70.8
Net C production (Gt/year)	33.26	8.51	2.70	8.40	24.62
Percentage	42.9	11.0	3.5	10.8	31.8
Standing C (Gt)	744	33.5	14.0	37.5	4.5
Percentage	89.3	4.0	1.7	4.5	0.5

Note. Adapted from Table 2.2 in Klass, D. L. (1998). "Biomass for Renewable Energy, Fuels, and Chemicals." Academic Press, San Diego, CA.

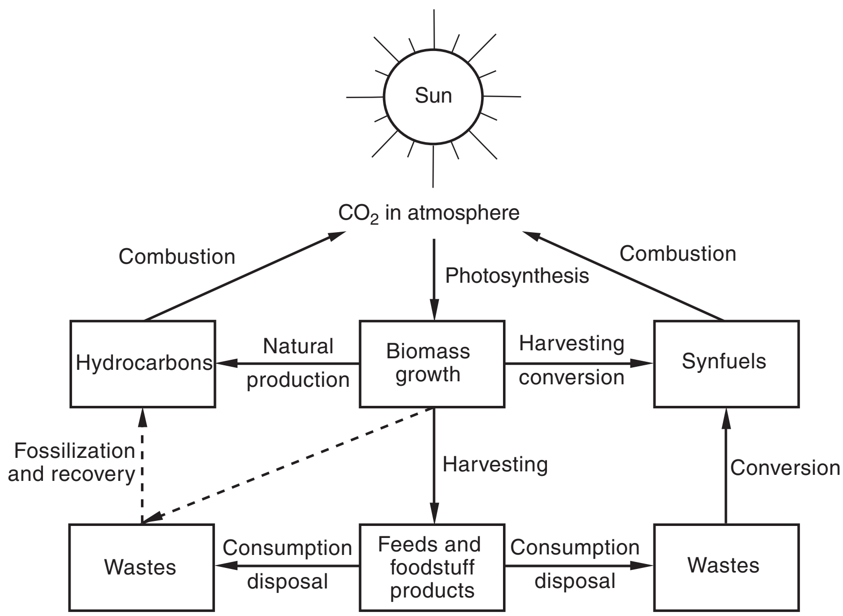

FIGURE 1 Main features of biomass energy technology. From Klass (1998).

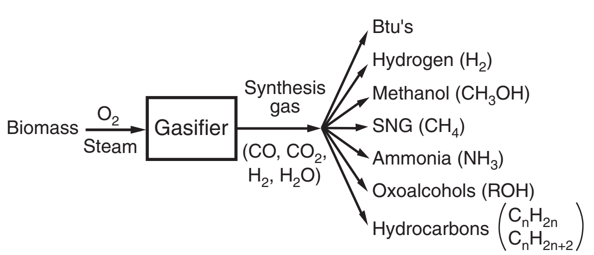

FIGURE 2 Chemicals from syngas by established processes. From Klass (1998).

850,000 barrels of oil equivalent per day (boe/day), or more than 2% of total primary energy consumption at that time. In 1990, when total U.S. primary energy consumption was about 88.9 EJ (84.3 quad), virgin and waste biomass resources contributed about 3.3% to U.S. primary energy demand at a rate of about 1.4 Mboe/day, as shown in Table III. By 2000, when total primary energy consumption had increased to 104.1 EJ (98.8 quad), virgin and waste biomass resources contributed about 23% more to primary energy demand, 1.60 Mboe/day, although the overall percentage contribution was about the same as in 1990 (Table IV).

According to the United Nations, biomass energy consumption was about 6.7% of the world's total energy consumption in 1990. For 2000, the data compiled by the International Energy Agency (IEA) from a survey of 133 countries indicate that biomass' share of total energy consumption, 430 EJ (408 quad), for these countries is about 10.5% (Table V). Although the IEA cautions that the quality and

TABLE III

Consumption of Biomass Energy in United States in 1990

Biomass resource	EJ/year	boe/day
Wood and wood wastes		
Industrial sector	1.646	763,900
Residential sector	0.828	384,300
Commercial sector	0.023	10,700
Utilities	0.013	6,000
Total	2.510	1,164,900
Municipal solid wastes	0.304	141,100
Agricultural and industrial wastes	0.040	18,600
Methane		
Landfill gas	0.033	15,300
Biological gasification	0.003	1,400
Thermal gasification	0.001	500
Total	0.037	17,200
Transportation fuels		
Ethanol	0.063	29,200
Other biofuels	0	0
Total	0.063	29,200
Grand total	2.954	1,371,000
Percentage primary energy consumption	3.3	

Note. From Klass, D. L. (1990). *Chemtech* **20**(12), 720–731; and U.S. Department of Energy (1991). "Estimates of U.S. Biofuels Consumption DOE/EIA-0548," October. Energy Information Administration, Washington, DC.

TABLE IV

Consumption of Biomass Energy in United States in 2000

Biomass resource	EJ/year	boe/day
Wood	2.737	1,270,100
Waste	0.570	264,800
Alcohol fuels	0.147	68,000
Total	3.454	1,602,900

Note. Adapted from Energy Information Administration (2002). *Monthly Energy Review,* August, Table 10.1. Washington, DC. Wood consists of wood, wood waste, black liquor, red liquor, spent sulfite liquor, wood sludge, peat, railroad ties, and utility poles. Waste consists of MSW, LFG, digester gas, liquid acetonitrile waste, tall oil, waste alcohol, medical waste, paper pellets, sludge waste, solid by products, tires, agricultural by-products, closed-loop biomass, fish oil, and straw. Alcohol fuels consist of ethanol blended into motor gasoline.

reliability of the data they compiled on biomass may be limited, which makes comparison between countries difficult, and that the proper breakdown between renewables and nonrenewables is often not available, it is clear that a significant portion of global energy consumption is based on biomass resources. It is also evident that the largest biomass energy consumption occurs among both industrialized and developing countries. Some countries meet a large percentage of their energy demands with biomass resources such as Sweden, 17.5%; Finland, 20.4%; Brazil, 23.4%; while many other countries in South America, Africa, and the Far East use biomass energy resources that supply much higher percentages of total energy demand. As expected, most countries in the Middle East where large proved crude oil and natural gas reserves are located and where dedicated energy crops might be difficult to grow meet their energy and fuel needs without large contributions from biomass resources.

The IEA reports that the share of energy consumption for renewables in 2000 was 13.8% of total energy consumption, of which 79.8% is combustible renewables and waste, most of which is biomass, and that the balance of 20.2% consists of hydroelectric power, 16.5%, and 3.7% other renewables.

Despite some of the inconsistencies that can occur because of data reliability, specific comparisons for total and biomass energy consumption in Table VI, and for total electricity and biomass-based electricity generation in Table VII, are shown for the eleven largest energy-consuming countries including the United States. The data for seven countries in these tables are for 2000; data for four countries are for 1999. The United States is the largest energy consumer, but China and India are the largest biomass energy consumers. Primary biomass solids as described in the footnote for Table VI are the largest biomass resources for these countries as well as the other countries listed in this table. In the case of electricity generation from biomass, the United States, Japan, and Germany are the largest producers of the 11 countries listed in Table VII, and the biomass resource most utilized is primary biomass solids for the United States and Japan, while Germany uses much less of that resource. It is surprising that China and India are each reported to use "0" biogas for power generation, since it is well known that each these countries operate millions of small-scale and farm-scale methane fermentation units, while many major urban cities utilize the high-methane fuel gas produced during wastewater treatment by anaerobic digestion. The lack of data is probably the cause of this apparent inconsistency.

It is noteworthy that some energy analysts have predicted that the end of seemingly unlimited petroleum crude oil and natural gas resources is in

TABLE V

Total Energy Consumption and Biomass' Share of Total Consumption for 133 Countries in 2000

Region	Country	Total consumption (Mtoe)	Total consumption (EJ/year)	Biomass' share total consumption (%)	Biomass' share total consumption (EJ/year)	Biomass' share total consumption (Mboe/day)
North America	Canada	251	10.9	4.5	0.491	
	Cuba	13.2	0.573	21.1	0.121	
	Dominican Republic	7.8	0.34	17.4	0.059	
	Haiti	2	0.09	75.4	0.068	
	Jamaica	3.9	1.5	12.1	0.182	
	Mexico	153.5	6.664	5.2	0.347	
	Panama	2.5	0.11	18.1	0.020	
	Trinidad and Tobago	8.7	0.38	0.4	0.002	
	United States	2300	99.85	3.4	3.395	
	Subtotal:	2742.6	120.41	3.9	4.685	2.100
South America	Argentina	61.5	2.67	4.4	0.117	
	Bolivia	4.9	0.21	14.7	0.031	
	Brazil	183.2	7.953	23.4	1.861	
	Chile	24.4	1.06	17.4	0.184	
	Colombia	28.8	1.25	18.3	0.229	
	Ecuador	8.2	0.36	8.5	0.031	
	El Salvador	4.1	0.18	34.0	0.061	
	Guatemala	7.1	0.31	54.5	0.169	
	Honduras	3	0.1	44.0	0.044	
	Netherlands Antilles	1.1	0.048	0.0	0.000	
	Nicaragua	2.7	0.12	51.6	0.062	
	Paraguay	3.9	0.17	58.2	0.099	
	Peru	12.7	0.551	17.6	0.097	
	Uruguay	3.1	0.13	13.7	0.018	
	Venezuela	59.3	2.57	0.9	0.023	
	Subtotal:	408.0	17.7	17.7	3.026	1.356
Europe	Albania	1.6	0.069	3.6	0.002	
	Austria	28.6	1.24	10.9	0.135	
	Belgium	59.2	2.57	1.2	0.031	
	Bosnia and Herzegovina	4.4	0.19	4.2	0.008	
	Bulgaria	18.8	0.816	3.1	0.025	
	Croatia	7.8	0.34	4.8	0.016	
	Cyprus	2.4	0.10	0.4	0.000	
	Czech Republic	40.4	1.75	1.5	0.026	
	Denmark	19.5	0.847	8.8	0.075	
	Finland	33.1	1.44	20.4	0.294	
	France	257.1	11.16	4.5	0.502	
	Germany	339.6	14.74	2.5	0.369	
	Gibraltar	0.2	0.009	0.0	0.000	
	Greece	27.8	1.21	3.7	0.045	
	Hungary	24.8	1.08	1.5	0.016	
	Iceland	3.4	0.15	0.0	0.000	
	Ireland	14.6	0.634	1.2	0.008	
	Italy	171.6	7.449	4.9	0.365	
	Luxembourg	3.7	0.16	0.8	0.001	

continues

Table V continued

Region	Country	Total consumption (Mtoe)	Total consumption (EJ/year)	Biomass' share total consumption (%)	Biomass' share total consumption (EJ/year)	Biomass' share total consumption (Mboe/day)
	Macedonia	2.8	0.12	7.7	0.009	
	Malta	0.8	0.03	0.0	0.000	
	Netherlands	75.8	3.29	2.3	0.076	
	Norway	25.6	1.11	5.3	0.059	
	Poland	90	3.9	4.5	0.176	
	Portugal	24.6	1.07	8.3	0.089	
	Romania	36.3	1.58	7.9	0.125	
	Russia	614	26.7	1.1	0.294	
	Slovak Republic	17.5	0.760	0.5	0.004	
	Slovenia	6.5	0.28	6.5	0.018	
	Spain	124.9	5.422	3.6	0.195	
	Sweden	47.5	2.06	17.5	0.361	
	Switzerland	26.6	1.15	6.0	0.069	
	United Kingdom	232.6	10.10	0.9	0.091	
	Fed. Rep. of Yugoslavia	13.7	0.595	1.8	0.011	
	Former Yugoslavia	35.1	1.52	1.8	0.027	
	Subtotal:	2432.9	105.6	3.3	3.522	1.579
Former USSR	Armenia	2.1	0.091	0.0	0.000	
	Azerbaijan	11.7	0.508	0.1	0.001	
	Belarus	24.3	1.05	4.1	0.043	
	Estonia	4.5	0.20	11.1	0.022	
	Georgia	2.9	0.13	2.5	0.003	
	Kazakhstan	39.1	1.70	0.1	0.002	
	Kyrgystan	2.4	0.10	0.2	0.000	
	Latvia	3.7	0.16	22.4	0.036	
	Lithuania	7.1	0.31	8.7	0.027	
	Republic of Moldova	2.9	0.13	2.0	0.003	
	Tajikistan	2.9	0.13	0.0	0.000	
	Turkmenistan	13.9	0.169	0.0	0.000	
	Ukraine	139.6	6.060	0.2	0.012	
	Uzbekistan	50.2	2.18	0.0	0.000	
	Subtotal:	307.3	13.34	1.1	0.149	0.067
Africa	Algeria	29.1	1.26	0.3	0.004	
	Angola	7.7	0.33	74.5	0.246	
	Benin	2.4	0.10	75.5	0.076	
	Cameroon	6.4	0.28	78.4	0.220	
	Congo	0.9	0.04	65.6	0.026	
	Cote d'lvoire	6.9	0.30	60.9	0.183	
	Egypt	46.4	2.01	2.8	0.056	
	Eritrea	0.7	0.03	70.9	0.021	
	Ethiopia	18.7	0.812	93.1	0.756	
	Gabon	1.6	0.072	59.2	0.043	
	Ghana	7.7	0.33	68.8	0.227	
	Kenya	15.5	0.239	76.1	0.182	
	Libya	16.4	0.712	0.8	0.006	
	Morocco	10.3	0.447	4.3	0.019	
	Mozambique	7.1	0.31	92.7	0.287	

continues

Table V continued

		Total consumption		Biomass' share total consumption		
Region	**Country**	**(Mtoe)**	**(EJ/year)**	**(%)**	**(EJ/year)**	**(Mboe/day)**
	Namibiae	1	0.04	16.8	0.007	
	Nigeria	90.2	3.92	80.2	3.144	
	Senegal	3.1	0.13	55.8	0.073	
	South Africa	107.6	4.671	11.6	0.542	
	Sudan	16.2	0.703	86.9	0.611	
	United Rep. of Tanzania	15.4	0.669	93.6	0.626	
	Togo	1.5	0.065	67.7	0.044	
	Tunisia	7.9	0.34	15.7	0.053	
	Zambia	6.2	0.27	82.2	0.222	
	Zimbabwe	10.2	0.443	54.8	0.243	
	Subtotal:	437.1	19.00	41.7	7.917	3.548
Middle East	Bahrain	6.4	0.28	0.0	0.000	
	Iran	112.7	4.893	0.7	0.034	
	Iraq	27.7	1.20	0.1	0.001	
	Israel	20.2	0.877	0.0	0.000	
	Jordan	5.2	0.23	0.1	0.000	
	Kuwait	20.9	0.907	0.0	0.000	
	Lebanon	5.1	0.22	2.5	0.006	
	Oman	9.8	0.43	0.0	0.000	
	Qatar	15.7	0.682	0.0	0.000	
	Saudi Arabia	105.3	4.571	0.0	0.000	
	Syria	18.4	0.799	0.1	0.001	
	Turkey	77.1	3.35	8.4	0.281	
	United Arab Emirates	29.6	1.28	0.1	0.001	
	Yemen	3.5	0.15	2.2	0.003	
	Subtotal:	457.6	19.87	1.6	0.327	0.147
Far East	Bangladesh	18.7	0.812	40.8	0.331	
	Brunei	2	0.09	0.9	0.001	
	China	1142	49.58	18.7	9.271	
	Taiwan	83	3.6	0.0	0.000	
	Hong Kong (China)	15.5	0.673	0.3	0.002	
	India	501.9	21.79	40.2	8.760	
	Indonesia	145.6	6.321	32.6	2.061	
	Japan	524.7	22.78	1.1	0.251	
	North Korea	46.1	2.00	1.1	0.022	
	South Korea	193.6	8.405	5.8	0.487	
	Malaysia	49.5	2.15	5.1	0.110	
	Myanmar	12.5	0.543	73.3	0.398	
	Nepal	7.9	0.34	85.2	0.290	
	Pakistan	64	2.8	37.6	1.053	
	Philippines	42.4	1.84	22.5	0.414	
	Singapore	24.6	1.07	0.0	0.000	
	Sri Lanka	8.1	0.35	52.8	0.185	
	Thailand	73.6	3.20	19.4	0.621	
	Vietnam	37	1.6	61.2	0.979	
	Subtotal:	2992.7	129.92	19.4	25.236	11.311

continues

Table V continued

Region	Country	Total consumption (Mtoe)	Total consumption (EJ/year)	Biomass' share total consumption (%)	Biomass' share total consumption (EJ/year)	Biomass' share total consumption (Mboe/day)
Oceania	Australia	110.2	4.784	4.9	0.234	
	New Zealand	18.6	0.807	6.5	0.052	
	Subtotal:	128.8	5.591	5.1	0.286	0.128
	Total:	9907	430.1	10.5	45.148	20.236

Note. Total energy consumption in Mtoe for each country listed was compiled by the International Energy Agency (2002). IEA's data for total energy consumption were converted to EJ/year (for 2000) in this table using a multiplier of 0.043412. The multiplier for converting EJ/year to Mboe/day is 0.4482×10^6. For each country, the IEA reported the total share of renewables as a percentage of the total consumption and as a percentage of the total consumption excluding combustible renewables and waste (CRW). Since CRW is defined to contain 97% commercial and noncommercial biomass, the percentage share of biomass for each country listed here is calculated as the difference between the percentage of total consumption and the percentage of CRW.

TABLE VI

Total Energy Consumption, Total Biomass Energy Consumption, and Biomass Energy Consumption by Biomass Resource in EJ/Year for United States and Top 10 Energy-Consuming Countries

Country	Total	Total biomass	Renewable MSW	Industrial wastes	Primary biomass solids	Biogas	Liquid biomass
United States	99.85	3.373	0.308	0.166	2.616	0.143	0.140
China*	47.25	9.244	0	0	9.191	0.054	0
Russia*	26.18	0.326	0	0.111	0.216	0	0
Japan	22.78	0.242	0.044	0	0.198	0	0
India*	20.84	8.596	0	0	8.596	0	0
Germany	14.74	0.366	0.076	0.045	0.213	0.024	0.007
France	11.16	0.496	0.079	0	0.399	0.008	0.011
Canada	10.9	0.487	0	0	0.487	0	0
United Kingdom	10.10	0.093	0.012	0.002	0.036	0.035	0
South Korea	8.405	0.092	0.065	0.015	0.007	0.002	0
Brazil*	7.80	1.862	0	0	1.547	0	0.322

Note. The energy consumption data for each country listed here were adapted from the International Energy Agency (2002). The data presented in Mtoe were converted to EJ/year using a multiplier of 0.043412. The data for those countries marked with an asterisk are for 1999; the remaining data are for 2000. Data reported as "0" by the IEA are shown in the table (see text). The sum of the energy consumption figures for the biomass resources may not correspond to total biomass energy consumption because of rounding and other factors (see text). The nomenclature used here is IEA's, as follows: biomass consists of solid biomass and animal products, gas/liquids from biomass, industrial waste, and municipal waste any plant matter that is used directly as fuel or converted into fuel, such as charcoal, or to electricity or heat. Renewable MSW consists of the renewable portion of municipal solid waste, including hospital waste, that is directly converted to heat or power. Industrial waste consists of solid and liquid products such as tires, that are not reported in the category of solid biomass and animal products. Primary biomass solids consists of any plant matter used directly as fuel or converted into other forms before combustion, such as feedstock for charcoal production. This latter category includes wood, vegetal waste including wood wastes and crops used for energy production. Biogas consists of product fuel gas from the anaerobic digestion of biomass and soild wastes—including landfill gas, sewage gas, and gas from animal wastes—that is combusted to produce heat or power. Liquid biomass includes products such as ethanol.

sight. Irreversible shortages of these fossil fuels are expected to occur before the middle of the 21st century because their proved reserves have been projected to be insufficient to meet demands at that time. Supply disruptions are expected to start first with natural gas. This is illustrated by using a reserves availability model to plot global proved natural gas reserves and five times the proved reserves versus year as shown in Fig. 3. Presuming this model provides results that are more valid over the long term than reserves-to-consumption ratios, the trend in the curves indicates that shortages of natural gas would be expected to occur in the early years of the 21st century and then begin to cause

TABLE VII

Total Electricity Generation, Total Biomass-Based Electricity Generation, and Biomass-Based Electricity Generation by Biomass Resource in TWh/Year for United States and Top 10 Energy-Consuming Countries

Country	Total	Total biomass	Renewable MSW	Industrial wastes	Primary biomass solids	Biogas
United States	4003.5	68.805	15.653	6.552	41.616	4.984
China*	1239.3	1.963	0	0	1.963	0
Russia*	845.3	2.075	0	2.045	0.030	0
Japan	1081.9	16.518	5.209	0	11.309	0
India*	527.3	0	0	0	0	0
Germany	567.1	10.121	3.688	3.946	0.804	1.683
France	535.8	3.290	1.995	0	0.949	0.346
Canada	605.1	7.379	0	0	7.379	0
United Kingdom	372.2	4.360	0.695	0	0.700	2.556
South Korea	292.4	0.396	0.361	0	0	0
Brazil*	332.3	8.519	0	0	8.519	0

Note: The electricity generation data for each country listed here were adapted from the International Energy Agency (2002). The data for those countries marked with an asterisk are for 1999; the remaining data are for 2000. Data reported as "0" by the IEA are shown in the table (see text). The data compiled by the IEA is defined as "electricity output." The sum of the electricity generation figures for the biomass resources may not correspond to total biomass electricity generation because of rounding and other factors (see text). The nomenclature used here is IEA's, as follows: biomass consists of solid biomass and animal products, gas/liquids from biomass, industrial waste and municipal waste, and any plant matter that is used directly as fuel or converted into fuel, such as charcoal, or to electricity or heat. Renewable MSW consists of the renewable portion of municipal solid waste, including hospital waste, that is directly converted to heat or power. Industrial waste consists of solid and liquid products, such as tires, that are not reported in the category of solid biomass and animal products. Primary biomass solids consists of any plant matter used directly as fuel or converted into other forms before combustion, such as feedstock for charcoal production. This latter category includes wood, vegetal waste including wood wastes and crops used for energy production. Biogas consists of product fuel gas from the anaerobic digestion of biomass and soild wastes—including landfill gas, sewage gas, and gas from animal wastes—that is combusted to produce heat or power. Liquid biomass includes products such as ethanol.

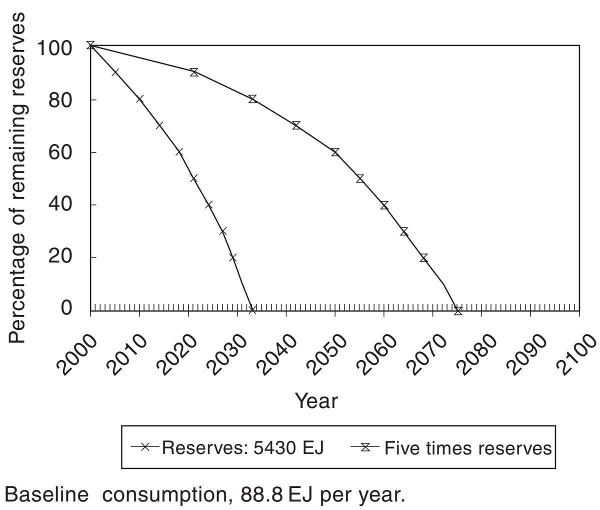

FIGURE 3 Global natural gas reserves remaining at annual growth rate in consumption of 3.2%. From Klass (2003). *Energy Pol.* **31**, 353.

serious supply problems in the next 20 to 30 years. Large-scale price increases for fossil fuels are probable because of what has been called the first derivative of the law of supply and demand, the law of energy availability and cost. This eventuality coupled with the adverse impacts of fossil fuel consumption on the environment are expected to be the driving forces that stimulate the transformation of virgin and waste biomass and other renewable energy resources into major resources for the production of energy, fuels, and commodity chemicals.

1.2 Biomass Composition and Energy Content

Typical organic components in representative, mature biomass species are shown in Table VIII, along with the corresponding ash contents. With few exceptions, the order of abundance of the major organic components in whole-plant samples of terrestrial biomass is celluloses, hemicelluloses, lignins, and proteins. Aquatic biomass does not appear to follow this trend. The cellulosic components are often much lower in concentration than the hemicelluloses as illustrated by the data for water hyacinth *(Eichhornia crassipes)*. Other carbohydrates

TABLE VIII

Organic Components and Ash in Representative Biomass

Biomass type	Marine	Fresh water	Herbaceous	Woody	Woody	Woody	Waste
Name	Giant brown kelp	Water hyacinth	Bermuda grass	Poplar	Sycamore	Pine	RDF
Component (dry wt %)							
Celluloses	4.8	16.2	31.7	41.3	44.7	40.4	65.6
Hemicelluloses		55.5	40.2	32.9	29.4	24.9	11.2
Lignins		6.1	4.1	25.6	25.5	34.5	3.1
Mannitol	18.7						
Algin	14.2						
Laminarin	0.7						
Fucoidin	0.2						
Crude protein	15.9	12.3	12.3	2.1	1.7	0.7	3.5
Ash	45.8	22.4	5.0	1.0	0.8	0.5	16.7
Total	100.3	112.5	93.3	102.9	102.1	101.0	100.1

Note. All analyses were performed by the Institute of Gas Technology (Gas Technology Institute). The crude protein content is estimated by multiplying the nitrogen value by 6.25. RDF is refuse-derived fuel (i.e., the combustible fraction of municipal solid waste).

and derivatives are dominant in marine species such as giant brown kelp *(Macrocystis pyrifera)* to almost complete exclusion of the celluloses. The hemicelluloses and lignins have not been found in *M. pyrifera*.

Alpha-cellulose, or cellulose as it is more generally known, is the chief structural element and major constituent of many biomass species. In trees, it is generally about 40 to 50% of the dry weight. As a general rule, the major organic components in woody biomass on a moisture and ash-free basis in weight percent are about 50 cellulosics, 25 hemicellulosics, and 25 lignins. The lipid and protein fractions of plant biomass are normally much less on a percentage basis than the carbohydrate components. The lipids are usually present at the lowest concentration, while the protein fraction is somewhat higher, but still lower than the carbohydrate fraction. Crude protein values can be approximated by multiplying the organic nitrogen analyses by 6.25. The sulfur contents of virgin and waste biomass range from very low to about 1 weight percent for primary biosolids. The sulfur content of most woody species of biomass is nil.

The chemical energy content or heating value is of course an important parameter when considering energy and fuel applications for different biomass species and types. The solid biomass formed on photosynthesis generally has a higher heating value on a dry basis in the range of 15.6 to 20.0 MJ/kg (6,700 to 8,600 Btu/lb), depending on the species. Typical carbon contents and higher heating values of the most common classes of biomass components are shown on a dry basis in Table IX. The higher the carbon content, the greater the energy value. It is apparent that the lower the degree of oxygenation, the more hydrocarbon-like and the higher the heating value. When the heating values of most waste and virgin biomass samples are converted to energy content per mass unit of carbon, they usually

TABLE IX

Typical Carbon Content and Heating Value of Selected Biomass Components

Component	Carbon (wt %)	Higher heating value (MJ/kg)
Monosaccharides	40	15.6
Disaccharides	42	16.7
Polysaccharides	44	17.5
Crude proteins	53	24.0
Lignins	63	25.1
Lipids	76–77	39.8
Terpenes	88	45.2
Crude carbohydrates	41–44	16.7–17.7
Crude fibers	47–50	18.8–19.8
Crude triglycerides	74–78	36.5–40.0

Note. Adapted from Klass, D. L. (1994). "Kirk-Othmer Encyclopedia of Chemical Technology," 4th ed., vol. 12, pp. 16–110. John Wiley & Sons. New York. Carbon contents and higher heating values are approximate values for dry mixtures; crude fibers contain 15 to 30% lignins.

fall within a narrow range. The energy value of a sample can be estimated from the carbon and moisture analyses without actual measurement of the heating values in a calorimeter. Manipulation of the data leads to a simple equation for calculating the higher heating value of biomass samples and also of coal and peat samples. One equation that has been found to be reasonably accurate is

$$\text{Higher heating value in MJ/dry kg} = 0.4571\ (\%\text{C on dry basis}) - 2.70. \qquad (3)$$

2. BIOMASS CONVERSION TECHNOLOGIES

2.1 Processes

The technologies include a large variety of thermal and thermochemical processes for converting biomass by combustion, gasification, and liquefaction, and the microbial conversion of biomass to obtain gaseous and liquid fuels by fermentative methods. Examples of the former are wood-fueled power plants in which wood and wood wastes are combusted for the production of steam, which is passed through a steam turbine to generate electricity; the gasification of rice hulls by partial oxidation to yield a low-energy-value fuel gas, which drives a gas turbine to generate electric power, and finely divided silica coproduct for sale; the rapid pyrolysis or thermal decomposition of wood and wood wastes to yield liquid fuel oils and chemicals; and the hydrofining of tall oils from wood pulping, vegetable oils, and waste cooking fats to obtain high-cetane diesel fuels and diesel fuel additives. Examples of microbial conversion are the anaerobic digestion of biosolids to yield a relatively high-methane-content biogas of medium energy value and the alcoholic fermentation of corn to obtain fuel ethanol for use as an oxygenate and an octane-enhancing additive in motor gasolines.

Another route to liquid fuels and products is to grow certain species of biomass that serve the dual role of a carbon-fixing apparatus and a natural producer of high-energy products such as triglycerides or hydrocarbons. Examples are soybean, from which triglyceride oil coproducts are extracted and converted to biodiesel fuels, which are the transesterified methyl or ethyl esters of the fatty acid moieties of the triglycerides having cetane numbers of about 50, or the triglycerides are directly converted to high-cetane value paraffinic hydrocarbon diesel fuels having cetane numbers of about 80 to 95 by catalytic hydrogenation; the tapping of certain species of tropical trees to obtain liquid hydrocarbons suitable for use as diesel fuel without having to harvest the tree; and the extraction of terpene hydrocarbons from coniferous trees for conversion to chemicals. A multitude of processes thus exists that can be employed to obtain energy, fuels, and chemicals from biomass. Many of the processes are suitable for either direct conversion of biomass or conversion of intermediates. The processes are sufficiently variable so that liquid and gaseous fuels can be produced that are identical to those obtained from fossil feedstocks, or are not identical but are suitable as fossil fuel substitutes. It is important to emphasize that virtually all of the fuels and commodity chemicals manufactured from fossil fuels can be manufactured from biomass feedstocks. Indeed, several of the processes used in a petroleum refinery for the manufacture of refined products and petrochemicals can be utilized in a biorefinery with biomass feedstocks. Note also that selected biomass feedstocks are utilized for conversion to many specialty chemicals, pharmaceuticals, natural polymers, and other higher value products.

2.2 Integrated Biomass Production-Conversion Systems

The energy potential of waste biomass, although of significant importance for combined waste disposal, energy-recovery applications, is relatively small compared to the role that virgin biomass has as an energy resource. The key to the large-scale production of energy, fuels, and commodity chemicals from biomass is to grow suitable virgin biomass species in an integrated biomass-production conversion system (IBPCS) at costs that enable the overall system to be operated at a profit. Multiple feedstocks, including combined biomass–fossil feedstocks and waste biomass, may be employed. Feedstock supply, or supplies in the case of a system that converts two or more feedstocks, is coordinated with the availability factor (operating time) of the conversion plants. Since growing seasons vary with geographic location and biomass species, provision is made for feedstock storage to maintain sufficient supplies to sustain plant operating schedules.

The proper design of an IBPCS requires the coordination of numerous operations such as biomass planting, growth management, harvesting, storage, retrieval, transport to conversion plants, drying, conversion to products, emissions control, product separation, recycling, wastewater and waste solids treatment and disposal, maintenance, and transmission or transport of salable products to market. The design details of the IBPCS depend on the feedstocks involved and the type, size, number, and location of biomass growth and processing areas needed. It is evident that a multitude or parameters are involved. In the idealized case, the conversion plants are located in or near the biomass growth areas to minimize the cost of transporting biomass to the plants, all the nonfuel effluents of which are recycled to the growth areas (Fig. 4). If this kind of plantation can be implemented in the field, it would be equivalent to an isolated system with inputs of solar radiation, air, CO_2, and minimal water; the outputs consist of the product slate. The nutrients are kept within the ideal system so that addition of external fertilizers and chemicals is not necessary. Also, the environmental controls and waste disposal problems are minimized.

It is important to understand the general characteristics of IBPCSs and what is required to sustain their operation. Consider an IBPCS that produces salable energy products at a rate of 10,000 boe/day from virgin biomass. This is a small output relative to most petroleum refineries, but it is not small for an IBPCS. Assume that the plant operates at an availability of 330 day/year at an overall thermal efficiency of converting feedstock to salable energy products of 60%, a reasonable value for established thermochemical conversion technologies. Equivalent biomass feedstock of average energy content of 18.60 GJ/dry tonne would have to be provided at the plant gate to sustain conversion operations at a rate of 5291 dry tonne/day, or a total of 1,746,000 dry tonne/year. This amount of feedstock, at an average biomass yield of 25 dry tonne/ha-year, requires a biomass growth area of 69,840 ha (270 square miles), or a square area 26.4 km (16.4 miles) on each edge. For purposes of estimation, assume the product is methanol and that no coproducts are formed. The total annual methanol production is then approximately 1.237 billion liters/year (327 million gallons/year). Fifty-four IBPCSs of this size are required to yield 1.0 quad of salable methanol energy per year, and the total growth area required is 3,771,400 ha (14,561 square miles), or a square area 194.2 km (120.7 miles) on each edge. Again exclusive of infrastructure and assuming the conversion facilities are all centrally located, the growth area is circumscribed by a radial distance of 101.4 km (68.1 miles) from the plants.

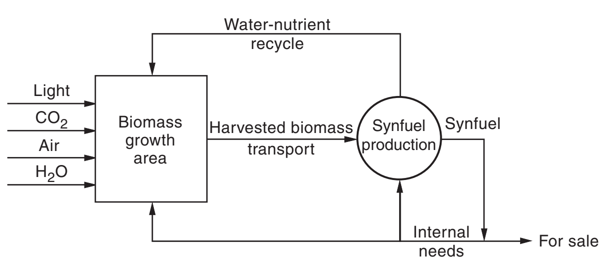

FIGURE 4 Idealized biomass growth and manufacturing system. From Klass (1998).

This simplistic analysis shows that the growth areas required to supply quad blocks of energy and fuels would be very large when compared with conventional agricultural practice, but that 10,000-boe/day systems are not quite so large when compared with traditional, sustainable wood harvesting operations in the forest products industry. The analysis suggests that smaller, localized IBPCSs in or near market areas will be preferred because of logistics and product freight costs, and multiple feedstocks and products will have advantages for certain multiproduct slates. For example, commercial methanol synthesis is performed mainly with natural gas feedstocks via synthesis gas. Synthesis gas from biomass gasification used as cofeedstock in an existing natural gas-to-methanol plant can utilize the excess hydrogen produced on steam reforming natural gas. Examination of hypothetical hybrid methanol plants shows that they have significant benefits such as higher methanol yields and reduced natural gas consumption for the same production capacity.

Sustainable virgin biomass production at optimum economic yields is a primary factor in the successful operation of IBPCSs. Methodologies such as no-till agriculture and short-rotation woody crop (SWRC) growth have been evaluated and are being developed for biomass energy and combined biomass energy-coproduct applications. Most of the IBPCSs that have been proposed are site specific—that is, they are designed for one or more biomass species, in the case of a multicropping system, for specific regions. Field trials of small IBPCSs or modules of IBPCSs are in progress in the United States, but no full-scale systems have yet been built. Some of the large, commercial forestry operations for tree growth, harvesting, and transport to the mills can be considered to be analogous in many respects to the biomass production phase of managed IBPCSs. The growth, harvesting, and transport of corn to fermentation plants for fuel ethanol manufacture in the U.S. Corn Belt is perhaps the closest commercial analog to an IBPCS in the United States. Most of the other large IBPCSs that have been announced for operation outside the United States are either conceptual in nature or have not been fully implemented.

The historical development of IBPCSs shows that large-scale biomass energy plantations must be planned extremely carefully and installed in a logical scale-up sequence. Otherwise, design errors and operating problems can result in immense losses and can be difficult and costly to correct after construction of the system is completed and operations have begun. It is also evident that even if the system is properly designed, its integrated operation can have a relatively long lag phase, particularly for tree plantations, before returns on investment are realized. The financial arrangements are obviously critical and must take these factors into consideration.

3. COMMERCIAL BIOMASS ENERGY MARKETS AND ECONOMICS

3.1 Some Examples

The United States only has about 5% of the world's population, but is responsible for about one-quarter of total global primary energy demand. The markets for biomass energy in the United States are therefore already established. They are large, widespread, and readily available as long as the end-use economics are competitive.

To cite one example, petroleum crude oils have been the single largest source of transportation fuels since the early 1900s in the United States. Because of undesirable emissions from conventional hydrocarbon fuels, the U.S. Clean Air Act Amendments of 1990 included a requirement for dissolved oxygen levels in unleaded gasoline of at least 2.7 weight percent during the four winter months for 39 so-called nonattainment areas. The Act also required a minimum of 2.0 weight percent dissolved oxygen in reformulated gasoline in the nine worst ozone nonattainment areas year-round. The largest commercial oxygenates for gasolines in the United States have been fermentation ethanol, mainly from corn, and MTBE, which is manufactured from petroleum and natural gas feedstocks. Oxygenated gasolines are cleaner burning than nonoxygenated gasolines, and the oxygenates also serve as a replacement for lead additives by enhancing octane value in gasoline blends.

U.S. motor gasoline production was about 473 billion liters (125 billion gallons) in 2000, during which total U.S. gasohol production was about 61.7 billion liters (16.3 billion gallons) if it is assumed that all domestically produced fuel ethanol from biomass feedstocks in 2000, 6.17 billion liters (1.63 billion gallons), was blended with motor gasolines as gasohol. MTBE has been a major competitor of fuel ethanol as an oxygenate and octane-improving additive for unleaded gasolines since the phase-out of leaded gasolines began in the 1970s and 1980s. Without reviewing the detailed reasons for it other than to state that leakage from underground storage tanks containing MTBE-gasoline blends has polluted underground potable water supplies, federal legislation is pending that would eliminate all MTBE usage in gasolines and establish a renewables energy mandate in place of an oxygenate mandate. The provisions of this mandate are expected to include the tripling of fuel ethanol production from biomass by 2012. MTBE would be prohibited from use in motor gasoline blends in all states within a few years after enactment of the legislation. If the mandate does not become federal law, the replacement of MTBE by fuel ethanol is still expected to occur because many states have already announced plans to prohibit MTBE usage. Other states are exploring the benefits and logistics of removing it from commercial U.S. gasoline markets.

The cost of fermentation ethanol as a gasoline additive has been reduced at the pump by several federal and state tax incentives. The largest is the partial exemption of $0.053/gallon for gasohol-type blends ($0.53/gallon of fuel ethanol), out of a federal excise gasoline tax of $0.184/gallon, and a small ethanol producers tax credit of $0.10/gallon. The purpose of these incentives is to make fermentation ethanol-gasoline blends more cost competitive. Without them, it is probable that the market for fuel ethanol would not have grown as it has since it was re-introduced in 1979 in the United States as a motor fuel component. With corn at market prices of $2.00 to $2.70/bushel, its approximate price range from 1999 to 2002, the feedstock alone contributed 20.3 to 27.4 cents/liter ($0.769 to $1.038/gallon) to the cost of ethanol without coproduct credits. In 1995–1996, when the market price of corn was as high as $5.00/bushel, many small ethanol producers had to close their plants because they could not operate at a profit.

An intensive research effort has been in progress in the United States since the early 1970s to improve the economics of manufacturing fermentation ethanol using low-grade, and sometimes negative-cost feedstocks such as wood wastes and RDF, instead of corn and other higher value biomass feedstocks. Significant process improvements, such as large reductions in process energy consumption, have been made during this research, but the target production cost of \$0.16/liter (\$0.60/gallon) has not yet been attained. It is believed by some that fuel ethanol production will exhibit even larger increases than those mandated by legislation, possibly without the necessity for tax incentives, when this target is attained.

Some cost estimates indicate that fuel ethanol as well as the lower molecular weight C_3 to C_6 alcohols and mixtures can be manufactured by thermochemical non-fermentative processing of a wide range of waste biomass feedstocks at production costs as low as 25 to 50% the cost of fermentation ethanol from corn. The C_3+ alcohols and mixtures with ethanol also have other advantages compared to ethanol in gasoline blends. Their energy contents are closer to those of gasoline; their octane blending values are higher; the compatibility and miscibility problems with gasolines are small to nil; excessive Reid vapor pressures and volatility problems are less or do not occur; and they have higher water tolerance in gasoline blends, which facilitates their transport in petroleum pipelines without splash blending. Splash blending near the point of distribution is necessary for fuel ethanol-gasoline blends.

Another example of a commercial biomass-based motor fuel is biodiesel fuel. It is utilized both as a cetane-improving additive and a fuel component in diesel fuel blends, and as a diesel fuel alone. Biodiesel is manufactured from the triglycerides obtained from oil seeds and vegetable oils by transesterifying them with methanol or ethanol. Each ester is expected to qualify for the same renewable excise tax exemption incentive on an equal volume basis as fuel ethanol from biomass in the United States. Unfortunately, the availability of biodiesel is limited. The main reason for the slow commercial development of biodiesel is the high production cost of \$75 to \$150/barrel caused mainly by the relatively low triglyceride yields per unit growth area, compared to the cost of conventional diesel fuel from petroleum crude oils.

In Europe, where the costs of motor fuels including diesel fuel are still significantly higher than those in the United States, the commercial scale-up of biodiesel, primarily the esters from the transesterification of rape seed triglycerides, has fared much better. Production is targeted at 2.3 million tonnes (5.23 billion liters, 1.38 billion gallons) in 2003, and 8.3 million tonnes (18.87 billion liters, 4.98 billion gallons) in 2010. Several European countries have established zero duty rates on biodiesel to increase usage and reduce greenhouse gas emissions from diesel-fueled vehicles.

Still another example of the commercial application of biomass energy is its use for the generation of electricity. U.S. tax incentives have been provided to stimulate and encourage the construction and operation of biomass-fueled power generation systems. Most of them are operated by independent power producers or industrial facilities, not utilities. The installed, nonutility electric generation capacity fueled with renewables in the United States and the utility purchases of electricity from nonutilities generated from renewable resources including biomass in 1995 by source, capacity, and purchases are shown in Table X. Note that the sums of the biomass-based capacities—wood and wood wastes, MSW and landfills, and other biomass—and purchases are about 43% and 57% of the totals from all renewable energy resources.

Unfortunately, several of the federal tax incentives enacted into law to stimulate commercial power generation from biomass energy have expired or the qualifying conditions are difficult to satisfy. In 2002, there were no virgin biomass species that were routinely grown as dedicated energy crops in the United States for generating electricity. There are many small to moderate size power plants, however, that are fueled with waste biomass or waste biomass-fossil fuel blends throughout the United States. These plants are often able to take credits such as the tipping fees for accepting MSW and RDF for disposal via power plants that use combustion or gasification as the means of energy recovery and disposal of these wastes, the federal Section 29 tax credit for the

TABLE X

Installed U.S. Nonutility Electric Generation Capacity from Renewable Energy Resources and Purchases of Electricity by Utilities from Nonutilities by Resource in 1995

Renewable resource	Capacity (GW)	Purchases (TWh)
Wood and wood wastes	7.053	9.6
Conventional hydro	3.419	7.5
MSW and landfills	3.063	15.3
Wind	1.670	2.9
Geothermal	1.346	8.4
Solar	0.354	0.8
Other biomass	0.267	1.5
Total	17.172	46.0

Note. Adapted from Energy Information Administration (1999). Renewable Energy 1998: Issues and Trends, DOE/EIA-0628(98), March, Washington, DC.

conversion to electricity of the LFG collected from landfills, the equivalent cost of purchased power generated from biogas in a wastewater treatment plant for on-site use, or the sale of surplus power to utilities by an IPP at the so-called avoided cost, which is the cost the utility would incur by generating the power itself.

3.2 Advanced Technologies

The research programs funded by the public and private sectors in the United States to develop renewable energy technologies since the First Oil Shock have led to numerous scientific and engineering advances for basically all renewable energy resources. Some of the advanced biomass-related technologies are listed here. Many of them have already been or will be commercialized.

- The development of hybrid trees and special herbaceous biomass species suitable for use as dedicated energy crops in different climates.
- Advanced plantation designs for the managed multicropping of virgin biomass species in integrated biomass production-conversion systems.
- Advanced biorefinery system designs for the sustained production of multiple product slates.
- Practical hardware and lower cost installation methods for recovering LFG from sanitary landfills for power generation and mitigation of methane emissions.
- Safety-engineered, unmanned LFG-to-electricity systems that operate continuously.
- High rate anaerobic treatment processes for greater destruction of pathogens and biosolids in wastewaters at higher biogas yields and production rates.
- Zero-emissions waste biomass combustion systems for combined disposal-energy recovery and recycling.
- Genetically engineered microorganisms capable of simultaneously converting all pentose and hexose sugars from cellulosic biomass to fermentation ethanol.
- Catalysts for thermochemical gasification of biomass feedstocks to product gases for conversion to preselected chemicals in high yields.
- Processes for the thermochemical conversion of waste and virgin biomass feedstocks to ethanol and lower molecular weight alcohols and ethers.
- Close-coupled biomass gasification-combustion systems for the production of hot water and steam for commercial buildings and schools.
- Advanced biomass gasification processes for the high-efficiency production of medium-energy-content fuel gas and power.
- Short-residence-time pyrolysis processes for the production of chemicals and liquid fuels from biomass.
- Catalytic processes for the direct conversion of triglycerides and tall oils to “super cetane” diesel fuels and diesel fuel additives having cetane numbers near 100.

3.3 Economic Impacts and Barriers

When full-scale, well-designed IBPCSs are in place in industrialized countries and are supplying energy, organic fuels, and commodity chemicals to consumers, conventional fossil fuel production, refining, and marketing will have undergone major changes. Numerous economic impacts are expected to occur. Biomass energy production and distribution will be a growth industry, while the petroleum and gas industries will be in decline. Because of the nature of IBPCSs, employment in agriculture and forestry and the supporting industries will exhibit significant increases over many different areas of the country. Unlike petroleum refineries, which are geographically concentrated in relatively few areas, and are therefore dependent on various long-distance modes of transporting refined products to market, the biomass energy industry will be widely dispersed in rural areas. Most IBPCSs will incorporate their own biorefineries. The transport distances of refined products to market will be relatively short, and the logistics of supplying energy demands will change. It is apparent that there will be many national and international impacts of the Renewable Energy Era.

The regional economic impact of biomass energy alone is illustrated by an assessment for the U.S. Southeast from which it was concluded that industrial wood energy generated 71,000 jobs and 1 billion dollars of income annually. It was estimated in another study that 80 cents of every dollar spent on biomass energy in a given region stays in the region, while almost all expenditures on petroleum products leave the region. Still another assessment conducted for the state of Wisconsin in the Midwest Corn Belt indicates the economic impacts of shifting a portion of Wisconsin’s future energy investment from fossil fuels to biomass energy. This study assumed a 75% increase in the state’s renewable energy use by 2010: 775 MW of new electric generating capacity to supply electricity to 500,000 Wisconsin homes and 379 million liters

(100 million gallons) per year of new ethanol production to supply gasohol to 45% of Wisconsin's automobiles. This scenario generated about three times more jobs, earnings, and sales in Wisconsin than the same level of imported fossil fuel usage and investment and was equivalent to 62,234 more job-years of net employment, $1.2 billion in higher wages, and $4.6 billion in additional output. Over the operating life of the technologies analyzed, about $2 billion in avoided payments for imported fuels would remain in Wisconsin to pay for the state-supplied renewable resources, labor, and technologies. Wood, corn, and waste biomass contributed 47% of the increase in net employment.

Nationwide, the projected economic impacts of biomass energy development are substantial. In 2001, with petroleum crude oil imports at about 9.33 million barrels/day, consumption of biomass energy and fuels corresponds to the displacement of 1.64 Mboe/day, or 17.6% of the total daily imports. This effectively reduces expenditures for imported oil, and beneficially impacts the U.S. trade deficit. Since agricultural crops and woody biomass as well as industrial and municipal wastes are continuously available throughout the United States, biomass also provides a strategic and distributed network of renewable energy supplies throughout the country that improve national energy security.

Conservatively, the energy and fuels available in the United States for commercial markets on a sustainable basis from virgin and waste biomass has been variously estimated to range up to about 15 quad per year, while the energy potentially available each year has been estimated to be as high as 40 quad. This is made up of 25 quad from wood and wood wastes and 15 quad from herbaceous biomass and agricultural residues. Utilization of excess capacity croplands of up to 64.8 million hectares (160 million acres) estimated to be available now for the growth of agricultural energy crops could open the way to new food, feed, and fuel flexibility by providing more stability to market prices, by creating new markets for the agricultural sector, and by reducing federal farm subsidy payments. Based on the parameters previously described for one-quad IBPCSs, this acreage is capable of producing about 17 quad of salable energy products from herbaceous feedstocks each year. Other opportunities to develop large IBPCSs exist in the United States using federally owned forest lands. Such IBPCSs would be designed for sustainable operations with feedstocks of both virgin and waste wood resources such as thinnings, the removal of which would also reduce large-scale forest fires that have become commonplace in the dryer climates, particularly in the western states.

Because of the multitude of organic residues and biomass species available, and the many different processing combinations that yield solid, liquid, and gaseous fuels, and heat, steam, and electric power, the selection of the best feedstocks and conversion technologies for specific applications is extremely important. Many factors must be examined in depth to choose and develop systems that are technically feasible, economically and energetically practical, and environmentally superior. These factors are especially significant for large-scale biomass energy plantations where continuity of operation and energy and fuel production are paramount. But major barriers must be overcome to permit biomass energy to have a large role in displacing fossil fuels.

Among these barriers are the development of large-scale energy plantations that can supply sustainable amounts of low-cost feedstocks; the risks involved in designing, building, and operating large IBPCSs capable of producing quad blocks of energy and fuels at competitive prices; unacceptable returns on investment and the difficulties encountered in obtaining financing for first-of-a-kind IBPCSs; and the development of nationwide biomass energy distribution systems that simplify consumer access and ease of use. These and other barriers must ultimately be addressed if any government decides to institute policies to establish large-scale biomass energy markets.

Without IBPCSs, biomass energy will be limited to niche markets for many years until oil or natural gas depletion starts to occur. The initiation of depletion of these nonrenewable resources may in fact turn out to cause the Third Oil Shock in the 21st century.

4. ENVIRONMENTAL IMPACTS

Several environmental impacts are directly related to biomass energy production and consumption. The first is obviously the environmental benefit of displacing fossil fuel usage and a reduction in any adverse environmental impacts that are caused by fossil fuel consumption. In addition, the use of a fossil fuel and biomass together in certain applications, such as electric power generation with coal and wood or coal and RDF in dual-fuel combustion or cocombustion plants, can result in reduction of undesirable emissions. The substitution of fossil fuels and their derivatives by biomass and biofuels also helps to conserve depletable fossil fuels.

Another beneficial environmental impact results from the combined application of waste biomass disposal and energy recovery technologies. Examples are biogas recovery from the treatment of biosolids in municipal wastewater treatment plants by anaerobic digestion, LFG recovery from MSW landfills, which is equivalent to combining anaerobic digestion of waste biomass and LFG "mining," and the conversion of MSW, refuse-derived fuel (RDF), and farm, forestry, and certain industrial wastes, such as black liquor generated by the paper industry, to produce heat, steam, or electric power. Resource conservation and environmental benefits certainly accrue from such applications.

Another environmental impact is more complex. It concerns the growth and harvesting of virgin biomass for use as dedicated energy crops. By definition, sustainable, biomass energy plantations are designed so that the biomass harvested for conversion to energy or fuels is replaced by new biomass growth. If more biomass is harvested than is grown, the system is obviously not capable of continued operation as an energy plantation. Furthermore, the environmental impact of such systems can be negative because the amount of CO_2 removed from the atmosphere by photosynthesis of biomass is then less that that needed to balance the amount of biomass carbon removed from the plantation. In this case, virgin biomass is not renewable; its use as a fuel results in a net gain in atmospheric CO_2. Energy plantations must be designed and operated to avoid net CO_2 emissions

TABLE XI

Estimated Annual Global Carbon Dioxide and Carbon Exchanges with the Atmosphere

	Carbon dioxide		Carbon equivalent	
Source or sink	To atmosphere (Gt/year)	From atmosphere (Gt/year)	To atmosphere (Gt/year)	From atmosphere (Gt/year)
Terrestrial				
Cement production	0.51		0.14	
Other industrial processes	0.47		0.13	
Human respiration	1.67		0.46	
Animal respiration	3.34		0.91	
Methane emissions equivalents	1.69		0.46	
Natural gas consumption	3.98		1.09	
Oil consumption	10.21		2.79	
Coal consumption	8.15		2.22	
Biomass burning	14.3		3.90	
Gross biomass photosynthesis		388		106
Biomass respiration	194		53	
Soil respiration and decay	194		53	
Total terrestrial	432	388	118	106
Oceans				
Gross biomass photosynthesis		180		49
Biomass respiration	90		25	
Physical exchange	275	202	75	55
Total oceans	365	382	100	104
Total terrestrial and oceans	797	770	218	210

Note. The fossil fuel, human, and animal emissions were estimated by Klass (1998). Most of the other exchanges are derived from exchanges in the literature or they are based on assumptions that have generally been used by climatologists. It was assumed that 50% of the terrestrial biomass carbon fixed by photosynthesis is respired and that an equal amount is emitted by the soil. The total uptake and emission of carbon dioxide by the oceans were assumed to be 104 and 100 Gt C/year (Houghton, R. A., and Woodwell, G. M. (1989). *Sci. Am.* **260**(4), 36) and biomass respiration was assumed to emit 50% of the carbon fixed by photosynthesis. The carbon dioxide emissions from cement production and other industrial processes are process emissions that exclude energy-related emissions; they are included in the fossil fuel consumption figures.

to the atmosphere. A few biomass plantations are now operated strictly to offset the CO_2 emissions from fossil-fired power plants, particularly those operated on coal. Sometimes, the fossil-fired power plant and the biomass plantation are geographically far apart. It is important to emphasize that established IBPCSs that utilize dedicated energy crops will normally involve the harvesting of incrementally new virgin biomass production.

Finally, there is the related issue of the causes of increasing concentrations of atmospheric CO_2, which is believed to be the greenhouse gas responsible for much of the climatic changes and temperature increases that have been observed. Most climatologists who have studied the problem portray atmospheric CO_2 buildup to be caused largely by excessive fossil fuel usage. Some assessments indicate that biomass contributes much more to the phenomenon than formerly believed, possibly even more than fossil fuel consumption. Because terrestrial biomass is the largest sink known for the removal of atmospheric CO_2 via photosynthesis, *the accumulated loss in global biomass growth areas with time and the annual reduction in global CO_2 fixation capacity* are believed by some to have had a profound adverse impact on atmospheric CO_2 buildup. The population increase and land use changes due to urbanization, the conversion of forest to agricultural and pasture lands, the construction of roads and highways, the destruction of areas of the rainforests, large-scale biomass burning, and other anthropological activities appear to contribute to atmospheric CO_2 buildup at a rate that is much larger than fossil fuel consumption. This is illustrated by the estimated annual global CO_2 exchanges with the atmosphere shown in Table XI. Despite the possibilities for errors in this tabulation, especially regarding absolute values, several important trends and observations are apparent and should be valid for many years. The first observation is that fossil fuel combustion and industrial operations such as cement manufacture emit much smaller amounts of CO_2 to the atmosphere than biomass respiration and decay and the physical exchanges between the oceans and the atmosphere. The total amount of CO_2 emissions from coal, oil, and natural gas combustion is also less than 3% of that emitted by all sources. Note that human and animal respiration are projected to emit more than five times the CO_2 emissions of all industry exclusive of energy-related emissions. Note also that biomass burning appears to emit almost as much CO_2 as oil and natural gas consumption together. Overall, the importance of the two primary sinks for atmospheric CO_2—terrestrial biota and the oceans—is obvious. No other large sinks have been identified.

Somewhat paradoxically then, it is logical to ask the question: How can large-scale biomass energy usage be considered to be a practical application of virgin biomass? The answer, of course, has already been alluded to. At a minimum, all virgin biomass harvested for energy and fuel applications must be replaced with new growth at a rate that is at least equal to the rate of removal. Even more desirable is the creation of additional new biomass growth areas, most likely forests, because they are the largest, long-lived, global reserve of standing, terrestrial biomass carbon. New biomass growth in fact seems to be one of the more practical routes to remediation of atmospheric CO_2 buildup.

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