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FUELS FROM BIOMASS AND WASTES

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PREFACE

As we approach the end of the twentieth century, the availability of fuel supplies continues to be a major determinant of economic growth and development. Increasing fossil energy costs and shortages are as inevitable as death and taxes. Some believe we are approaching the twilight of the fossil fuel era and that we are now in the process of returning to the use of nonfossil, renewable energy sources derived directly or indirectly from the sun. Those energy scientists and engineers that have a clean crystal ball (or, possibly, a dirty one, since the complete story has not yet been told), who adopted this position in the early 1970s, decided to resurrect an old but nevertheless feasible technology for harvesting chemically fixed solar energy for the production of organic fuels and chemicals. The intermediate raw material is biomass—land- and water-based vegetation in the form of trees, grasses, plants and algae—which can be converted to a broad range of useful energy forms. This idea makes sense because as a first approximation, the net annual biomass energy stored worldwide is about ten times the total energy used by man each year.

This book evolved from a symposium on this subject—fuels from biomass—sponsored by the American Chemical Society, Division of Fuel Chemistry Inc. and Division of Industrial and Engineering Chemistry, and the American Institute of Chemical Engineers at the Second Chemical Congress of the North American Continent in Las Vegas, Nevada, August 24–29, 1980. This meeting was a one-of-a-kind event because just two weeks before the conference began, it was moved from San Francisco to Las Vegas, a move which was beyond our control. Travel schedules and hotel reservations were rearranged at the last minute. Thus, a good percentage of the symposium audience was lost, but most of the speakers were on hand to make their presentation. We thank all the speakers and we are extremely grateful for their participation in the symposium.

All 18 papers on the symposium program, suitably revised, and 13 invited papers are included in this book. They are organized into chapter groupings: Introduction, Biomass Procurement and Production, Biological and Thermal Gasification, Hydrolysis and Extraction, Fermentation Ethanol, Natural and Thermal Liquefaction, Environmental Effects, and Systems and Case Studies. Many of the chapters have extensive reference lists which serve as an entree to the literature on the subject addressed. It is apparent that the technology of renewable energy from biomass and wastes is advancing on all fronts. We expect this source of primary energy will meet more and more of our energy and chemical needs as time passes. In our opinion, this course of events is also inevitable.

Donald L. Klass
George H. Emert

Donald L. Klass is Vice President of the Institute of Gas Technology (IGT), which has conducted energy education and research programs since 1941. Dr. Klass administers basic research and grants conducted by staff and graduate students, IGT's academic and industrial education programs, and contract education services. His research and development experience has been concentrated on petrochemical and refinery processes, fuels and lubricants, conversion of biomass and wastes to synthetic fuels, and gas processing. Dr. Klass' publications number over 200 papers and patents in these fields. He received his BS in chemistry at the University of Illinois and his AM and PhD degrees in organic chemistry at Harvard University.

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Dr. Emert received his bachelor's degree from the University of Colorado, his Master of Science from Colorado State University, and his doctorate in biochemistry and nutrition at Virginia Polytechnic Institute and State University. Dr. Emert's current efforts include scaling-up cellulose-to-ethanol technology to demonstration plant operating level.

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CHAPTER 1

FUELS FROM BIOMASS AND WASTES —AN INTRODUCTION

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THE CONCEPT

The concept of producing synfuels and energy products from biomass and wastes is a simple one, as shown in Figure 1. The capture of solar energy as fixed carbon in organic plant material via photosynthesis is the key initial step in this scheme and is represented by the equation:

$$CO_2 + H_2O + \text{light} \xrightarrow{\text{chlorophyll}} (CH_2O) + O_2$$

Carbohydrate is the primary product. For each gram atom of carbon fixed, about 470 kJ (112 kcal) are absorbed. Oxygen liberated in the process comes exclusively from the water, according to radioactive tracer studies. Although there are still many unanswered questions regarding the detailed molecular mechanisms of photosynthesis, the prerequisites for biomass production are well established; carbon dioxide, water, light in the visible region of the electromagnetic spectrum, a sensitizing catalyst and a living plant are essential. The upper limit of the capture efficiency of the incident solar radiation in biomass has been variously estimated to range from about 8% to as high as 15%, but in most real situations, it is generally in the 1% or less range.

The idea of using biomass as a raw material for conversion to synfuels and energy products is certainly not a new one. Wood was a major

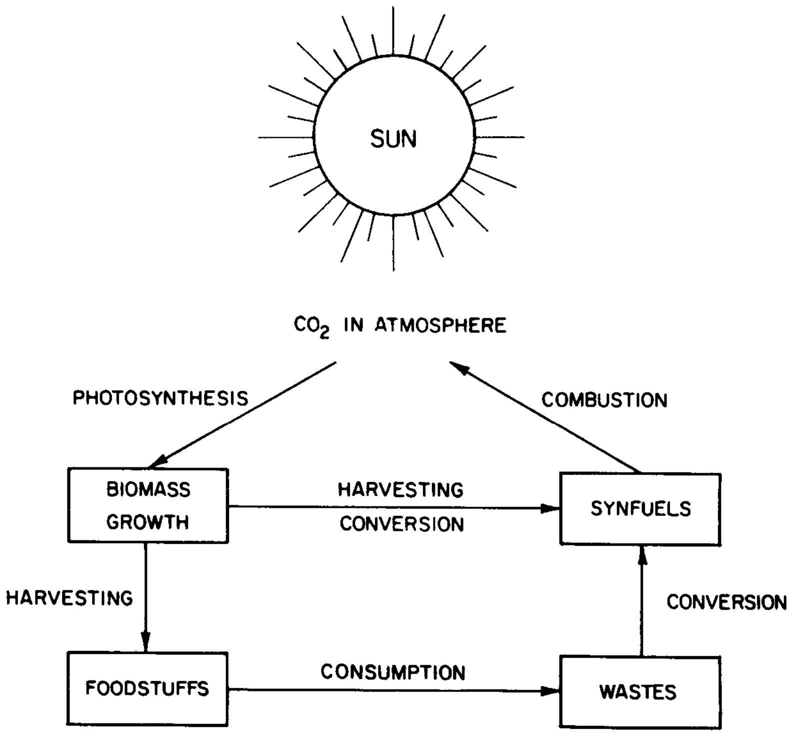

Figure 1. Schematic representation of synfuel production from biomass and wastes.

source of primary energy for the United States only a relatively few years ago (Figure 2). The main difference between this "old technology" and the concept as it is being developed today is that we are applying more advanced methodologies and processes to produce organic fuels and chemicals in more desirable forms. To be sure, however, combustion of certain biomass and wastes for heat, steam, and electric power production also an important application of nonfossil renewable carbon and will continue to grow.

The reasons for utilizing biomass and wastes as energy resources are numerous. Some of the more obvious ones are:

- Nonfossil forms of fixed carbon are not depletable, in contrast to fossil fuels such as oil, natural gas and coal.
- Biomass is available in large quantities, and provides a raw material for conversion to major supplies of synfuels.

- Combining waste disposal and energy recovery processes offers recycling opportunities as well as improved disposal technology, often at lower cost.
- A synfuels industry based on biomass and wastes is independent of foreign price controls and regulations.
- Technological breakthroughs are not required to develop commercial systems and processes.

These are some of the more important reasons why momentum to develop nonfossil carbon-to-energy technology is increasing. The purpose of this chapter is to introduce the subject and to summarize the many technologies now under development and in commercial use.

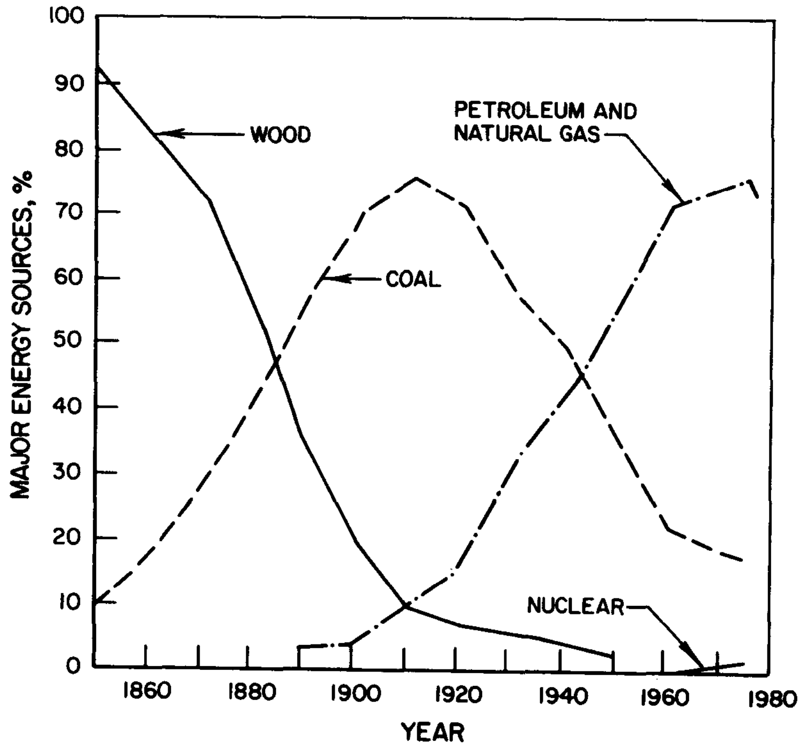

Figure 2. Historical U.S. energy consumption pattern.

ENERGY IMPACT

As might be expected, recent U.S. projections of the potential of energy from biomass and wastes span the entire range from small to large impact. One of the forecasts made by the Office of Technology Assessment (OTA) indicated that in the year 2000, as few as 4–6 quads (1 quad = 10^{15} Btu = 1.05×10^{18} J), or as many as 12–17 quads could be derived from biomass and selected wastes depending on cropland availability, crop yield improvements, the development of efficient conversion processes and the level of policy support [1]. The high estimate was made up of 10 quads from wood, 0–5 quads from grasses and legume herbage (depending on cropland needs for foodstuffs), 1 quad from crop residues, 0.3 quad from manure (as methane) and 0.2 quad from grains (as ethanol); more details are shown in Table I for the years 1985 and 2000.

Table I. OTA Estimates for Biomass Energy Contribution in 1985 and 2000[a]

		Gross Energy Potential	
Feedstock	Source	1985 (quads)	2000 (quads)
Wood	Commercial forestland including mill wastes	3–5	10
Grass and Legume Herbage	Hayland, cropland pasture, non-cropland pasture	1–3[b]	0–5[b]
Crop Residues	Cropland used for intensive agriculture	0.7–1	0.8–1.2
Grain and Sugar Crops	(For ethanol production)	0.08–0.2[b]	0–1[b]
Grass and Short-Rotation Trees		0.3–1.6[b]	0–5[b]
Manure	Confined animal operations	0.1	0.1–0.3
Other Agricultural Wastes	Processing operations	0.1	0.1
Total		5.3–11	6–17

[a]Adapted from Reference 1. Does not include deductions for cultivation and harvest energy, losses or end-use efficiency.
[b]Not additive because they use some of same land.

OTA's higher estimate of the contribution of biomass energy in the year 2000 is four to six times that of a recent estimate of the U.S. Department of Energy (DOE) [2], but it should be noted that DOE's rather pessimistic estimate (3 quad/yr) is less than twice the current commercial contribution of wood energy alone (1.8 quad/yr; 850,000 barrels oil equivalent per day) [3]. DOE's forecast is also quite inconsistent when viewed in the context of the large federal investment to develop and commercialize biomass energy. Indeed, DOE's Office of Alcohol Fuels has a production goal of 3.0 quads of fuel ethanol alone by the year 2000 (Table II).

Despite the uncertainties encountered in conducting energy forecasts, they are still necessary to determine which of the various renewable organic raw materials have the greatest potential and the magnitude of the contribution that energy from biomass and wastes can make to meet future U.S. demands. Most energy forecasts are subject to continuous revision, particularly when there is a major technological improvement that decreases costs or when there is substantial price increase in competitive fuels.

Table II. Fuel Ethanol Production Goals of DOE Office of Alcohol Fuels

Year	Production Goals		Percent of 1978 Gasoline Consumption[b]	Capital Investment Required ($ billion)	Quads[c]
	10^9 liter/yr	bbl/day[a]			
1980	1.21	20,900	0.3	0.64	0.02
1981	1.89	32,600	0.5	1.1	0.04
1982	3.48	60,000	0.8	2.2	0.07
1985	7.57	130,000	1.8	5.7	0.15
1990	37.85	652,000	9.1	28.5	0.76
2000	151.4	2,610,000	36	100	3.0

[a]One bbl = 42 gal = 159 liters.

[b]U.S. gasoline consumption in 1978 was 110 billion gal (7.2 million bbl/day). Percent of gasoline consumption calculated on basis of replacement of equivalent volume of gasoline by ethanol.

[c]Calculated on basis of 21.08 MJ/l (75,000 Btu/gal) ethanol heating value.

On a worldwide basis, traditional fuel forms of biomass and wastes such as firewood, wood-derived charcoal, crop residues and dried animal dung now supply large portions of the total energy used—50–65% in Asia and 70–90% in Africa—and overall, they account for about 8.5 million barrels of oil-equivalent per day, or approximately 20–25% of energy consumption in the developing world [4]. Biomass and wastes have also been targeted to supply large portions of the energy demand in Europe. For example, a national program has been launched in France to obtain about 8–10% of its energy needs from biomass by 1990 [5]. Other European countries are developing similar plans.

BIOMASS PRODUCTION

Silviculture

Activities on tree species selection (Table III), from accumulated data, and management techniques for wood fuel farms are in progress, and emphasis is being given to the costs of different production strategies, improvement of existing forest stands, development of specialized harvesting equipment and the assessment of environmental effects [6]. The maximum delivered wood cost in the DOE program is targeted at \$25.00/green metric ton (\$22.68/green ton) [6]. This corresponds to a cost of about \$2.87/GJ (\$3.02/10^6 Btu) for green wood at 50 wt % moisture content and heating value of 17.43 GJ/metric ton (15 $\times$ 10^6 Btu/dry short ton).

Table III. Candidate Woody Biomass Species for Growth in the United States as Energy Crops [6]

Northeast and North Central	
Hybrid Poplar	American Sycamore
Black Locust	Boxelder
Black Alder	Sugar Maple
Willow Species	Ash Species
Eastern Cottonwood	Birch Species
South	
Hybrid Poplar	American Sycamore
Black Locust	Slash Pine
Tree of Heaven	Sand Pine, Loblolly Pine
Sweet Gum	Australian Pine
Eucalyptus	Chinese Tallow Tree
Great Plains	
Black Locust	Eastern Cottonwood
Ash Species	Silver Maple
Elm Species	Catalpa
Northwest	
Black Cottonwood	Red Alder
Southwest	
Athel Tree	Rabbitbush
Salt Cedar	Greasewood
Mesquite	Big Sagebrush
Palo Verde	Creosote Bush
Jojoba	Lucaena
Saltbush	Ironwood
Hawaii	
Eucalyptus	Mimosa

For energy applications, it has generally been felt that short-rotation coppice growth would provide the maximum amount of biomass carbon in the shortest time. Data are now being published that will permit real comparisons to be made of short-rotation growth with other silviculture methods. The results of an exemplary study are shown in Table IV [7]. Harvesting of American sycamore in this field test gave average aboveground yields of 7.1 and 9.7 oven-dry metric ton/ha-yr (2.9 and 4.0 short ton/ac-yr) at one- and two-year rotations, while the average yield was 10.9 oven-dry metric ton/ha-yr (4.5 short ton/ac-yr) for only one harvest in four years; spacing had little effect. Additional growth data are being collected, but these results suggest that the optimum rotation has not yet been selected for this particular field test. The incremental yield improvement at the optimum rotation must of course justify the additional cost and energy expenditures of more frequent harvesting before short-rotation coppice growth methods are used on a large scale for wood fuel farms.

Table IV. Aboveground Biomass (dry metric ton/ha-yr) (without Foliage) of American Sycamore at Different Rotations in the South [7]

Spacing and Rotation	Growing Season after Initial Coppice				Four-Year Total
	First	Second	Third	Fourth	
0.3 × 1.2 m					
1 yr	4.4	7.1	7.8	7.4	26.7
2 yr		14.0		19.5	33.5
4 yr				49.5	49.5
0.6 × 1.2 m					
1 yr	4.4	9.2	8.0	6.5	28.1
2 yr		15.1		24.3	39.4
4 yr				28.8	28.8
1.2 × 1.2 m					
1 yr	4.0	9.0	9.1	8.2	30.3
2 yr		16.5		27.1	43.6
4 yr				52.4	52.4

Nonwoody Herbaceous Plants

Some of the nonwoody herbaceous plants considered as potential energy crops from the production standpoint are the sorghums [8]; sugarcane [9]; sugar beets [10]; the arid and semi arid land plants