

66293

ERG-MR4e

ENERGY RESEARCH GROUP

ERG

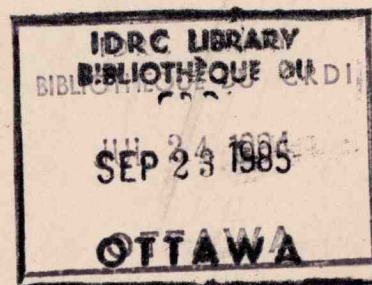
MANUSCRIPT REPORTS

Alternative Liquid Fuels

R.P. Overend;

M. Moo-Young, C.W. Robinson,
and Robert Lencki

**ARCHIV
66293**



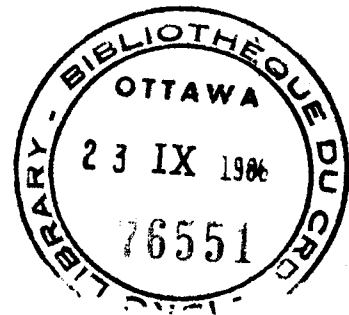
June 1984

The Energy Research Group consists of eminent members of the international community of energy analysts and policymakers from developing countries. This independent Group has been set up to review energy-related research and technology and its relevance to developing countries, to assess the research capacity of developing countries, and to suggest the priorities for energy research in these countries.

This series includes seminar papers, internal documents, and preliminary studies that may later form the basis of a formal publication. The copyright rests with the International Development Research Centre and the United Nations University, who are the joint sponsors of the Energy Research Group. However, the views expressed are those of the authors themselves, and not necessarily of the Centre or the University. This report is circulated by the Coordinator, The Energy Research Group, P.O. Box 8500, Ottawa K1G 3H9, Canada.

ALTERNATIVE LIQUID FUELS

R.P. Overend;
M. Moo-Young, C.W. Robinson, and Robert Lencki



ARCHIV
620.9
E 59.
no. 4

CONTENTS

Introduction	Ashok V. Desai	3
Bioenergy conversion systems: Current status	R.P. Overend	7
Liquid fuels from renewable resources: Technoeconomic comparisons of alternative feedstock uses	M. Moo-Young, C.W. Robinson, and Robert Lencki	23



INTRODUCTION

Ashok V. Desai

Coordinator, Energy Research Group
P.O. Box 8500, Ottawa
Ontario, Canada

Liquid fuels have a number of advantages. Being fluid, they are easier to store, handle, and transport than solid fuels; the range of hydrocarbons in current use also has greater energy density than low-cost solid substitutes like coal, lignite, and wood. They are cheaper to store and handle than gases, which need to be segregated from air and pressurized. Above all, they are the fuels used in the internal combustion engine, whose sturdiness, versatility, and capacity for size variation have multiplied its uses, and have led it to dominate land and air transport. Although the prospective exhaustion of mineral oil has spurred the search for alternatives, liquid fuels that can be used in internal combustion engines have a special appeal because they would not require the scrapping of the vast investments made in vehicles and in the factories to make them.

For this reason, two bioenergy specialists, Professor Murray Moo-Young and Dr. Ralph Overend, were asked to address the Energy Research Priorities Seminar in Ottawa on 9 August 1983. Their papers, put together in this publication, are based on North American experience, but are of considerable methodological interest.

In the present state of knowledge, no other liquid fuel is clearly cheaper than petroleum-based transport fuels, and most of them look so uncompetitive that private investors are not inclined to invest even in improving the state of knowledge. However, the governments of countries that have experienced insecurity in oil supply or balance of payments difficulties arising from the cost of oil imports have from time to time invested in research and development (R&D) and the commercialization of alternative liquid fuels. Two of them are being currently produced.

Catalytic hydrogenation is the basis of the production of synthetic oil from coal in the Sasol plant in South Africa. Coal forms a good feedstock because of its low cost and large volume of production. However, oil produced by catalytic hydrogenation will remain expensive because of its large hydrogen requirements, and the technology is operationally difficult owing to the high pressures and temperatures, the messiness of coal, and the trickiness of catalysts (Lee 1979).

Enzymatic hydrolysis is the basis of the production of ethanol from sugar cane in Brazil. The technology is much less demanding than that of coal hydrogenation: sugar cane is a more standardized feedstock than coal, the temperature and pressures are more moderate, breakdowns are less frequent, and a wide range of production scales is feasible.

Both solutions have much to do with the circumstances of the countries that have adopted them. The repression of its majority black population has earned the government of South Africa hostility among the nonwhite nations of the world; because these countries produce most of the exportable oil in the non-Communist world, South Africa obtains its oil only by the connivance of some of them and the cooperation of some oil companies. South Africa has reason to feel insecure about both the connivance and the cooperation, and to subsidize the production of high-cost coal-based oil.

Brazil was using over a third of its export earnings to pay for oil in 1974. The markets abroad for its sugar were depressed in 1975 and it made sense to use sugarcane to produce alcohol that would replace imported oil instead of exports that could not be sold (Goldemberg 1982).

South Africa's case is unique; Brazil's is common to many developing countries. A World Bank survey of 39 oil-importing developing countries in 1980 revealed that payments for net oil imports took over 50% of merchandise export earnings in 7 countries (18%) and between 25 and 50% in 17 countries (44%) (World Bank 1983).

In the light of the limited experience of oil-substitute production, an interested country or enterprise must rely on guesses regarding costs and quality. Overend shows a way of making such guesses using the available information. As he points out, there are at least three liquid fuels that can be used in vehicles: ethanol, methanol, and esterified vegetable oils. These can be used only as extenders in unmodified internal combustion engines; and all would require tailoring to particular specifications to make them fit for vehicular use (Anonymous 1980). There are two major routes to ethanol: enzymatic and acid hydrolysis. Ethanol can be made from many types of vegetal biomass including forest waste, agricultural residues, and aquatic biomass. Methanol is normally made from synthesis gas, which can be produced from a number of carbonaceous materials including coal, forest wastes, and agricultural residues. The large variety of materials, processes, and products make a comparison of costs essential.

Costs are conventionally classified into capital costs, incurred before production can begin, and running costs. Estimates of both get firmer as experience accumulates through research, development, pilot plant, and commercial plant. According to Overend, the capital costs of ethanol are in the same range for enzymatic and acid hydrolysis, but the former achieves higher efficiency of energy conversion. Energy efficiency is even higher in methanol production, but capital costs are also distinctly higher.

A high proportion of running costs, as Overend shows, consists of the cost of the feedstock. Here one is apt to think in industrial countries of waste materials such as wood waste, sawdust, straw, and animal waste, whose cost in situ is zero (or negative if they are a nuisance); however, the costs of collection are high, and increase with the dispersion of the feedstock. Developing countries have smaller quantities of such wastes available, which are often being used as fuel or manure and are hence not available at zero cost. Hence the argument is stronger in developing countries for growing a feedstock such as sugarcane or cassava; the greater the yields of such a crop, the lower the costs of its collection. The economies of concentration are just as strong in developing as in industrial countries.

Because of the importance of feedstock in running costs, every country tends to consider those feedstocks that are surplus. Thus Brazil settled on sugarcane as feedstock for ethanol, the USA uses mainly maize, and Canada is chiefly interested in wood. The cellulose and lignin in wood offer a more difficult feedstock for enzymatic hydrolysis than starch, and need pretreatment. As a result, Moo-Young finds wood-based ethanol uncompetitive in Canada unless by-products turn out to be remunerative. Wood is easily gasified and might be better turned into methanol.

Assuming that it is decided to hydrolyse wood, it can produce a number of products besides ethanol, and Moo-Young asks which of them would be the most profitable. He finds a few, such as citric acid and furfural, which are more profitable than ethanol, but their markets in the USA are small. However, the economics of ethanol depend greatly on the prices at which its joint products can be sold. The suggestion tossed out by Moo-Young that "high-priced potable beverage-grade ethanol should be produced instead of the cheaper full-grade variety" may be taken half seriously. But far more serious is his basic point that the broadest options should be considered. Instead of asking: what should replace imported oil? It may be more intelligent to ask: what are the resources? What can they produce? Of the products, which can be exported or can replace imports with the highest returns? The objective for a country must be to improve its balance of payments most effectively, and not simply to replace oil. The world, however, has no balance of payments with the rest of the universe, and cannot overcome the scarcity of oil by trading.

References

Anonymous. 1980. Use of alcohol fuels. In Energy from biological processes: Vol. II - Technical and environmental analyses. Office of Technology Assessment, United States Congress, Washington, DC, USA. p 201-218.

Goldemberg, J. 1982. Energy issues and policies in Brazil. Annual Review of Energy 7, p 139-174.

Lee, E. Stanley. 1979. Coal liquefaction. In Wen, C.Y. and Lee, E. Stanley, ed., Coal conversion technology. Addison-Wesley Publishing Co., Reading, MA, USA. p 428-545.

World Bank, 1983. The energy transition in developing countries. The World Bank, Washington, DC, USA.

BIOENERGY CONVERSION SYSTEMS: CURRENT STATUS

R.P. Overend*

Biomass¹ conversion to energy and bioenergy is a subject of interest to both industrialized and developing countries in obtaining the maximum return on their natural resource bases. This report is based on recent undertakings at the National Research Council (NRC) of Canada in reviewing International Energy Agency (IEA) bioenergy programs and preparing technology assessments in this field.

The interests of the Organization for Economic Cooperation and Development (OECD) and the Less Developed Countries (LDCs) do not always coincide if the potential of biomass energy is viewed from the perspective of the resource base. In fact, many OECD countries are trying to solve problems of foodstuff surpluses by the use of bioenergy or the withdrawal of land by PIK (Payment in Kind) subsidies whereas, for many of the LDCs, there are both food and firewood crises. The general opportunity for bioenergy in OECD nations is in exploitation of residues generated in the food and fibre production and processing systems. Such residues have often been disposed of in an environmentally poor fashion and treated as wastes from the economic perspective. If energy crops are considered, they are generally seen as a response to surplus foodstuff production -- as in the recent European Parliament resolution to look at the option of transferring 30×10^6 ha of land from food to alcohol production. For LDCs, the residue availability is a major consideration and current use for fuel is often environmentally nonproductive. Trees and other lignocellulosics are often harvested directly for fuel and charcoal production.

Bioenergy conversion systems are more universal in use. The conversion processes are the transformers linking the heterogeneous resource to the end uses that are, in the main, conditioned by the existing energy carriers and utilization patterns. This is generally true for both the OECD and LDC nations because it is only in a few countries that the bioenergy contribution can exceed 5% of the primary energy supply. This characteristic of bioenergy, which requires taking account of the existing major energy carriers such as electricity, gas, and petroleum, is at one and the same time a strength and a weakness as I will elaborate later.

General Description of the State-of-the-Art in Bioenergy Conversion

Conversion technology: Industrial-scale systems

Combustion systems have been developed and commercialized for dry forest and agricultural residues that span the capacity range between the domestic heating system and the 30-MW_{th} size range. The modern systems generally have high efficiencies with good compliance to environmental emissions standards. In general, they are not as simple in use as the traditional fossil-fueled systems and their capital cost per unit output is often three to eight times that of the oil- or natural gas-fired alternative. This restricts the competitiveness of these systems because they are only profitable with relatively low-cost feedstocks. In many countries, commercialization of densified biomass fuels has permitted the use of retrofitted burners to existing heating systems.

* National Research Council of Canada, Ottawa, Ont., Canada

¹ A number of terms used here are defined in the appendix (page 21).

Gasification has been proven at a demonstration level in applications such as boiler retrofit, crop drying, and internal combustion (IC) engine-powered electrical-generator uses. Several companies are marketing such systems in both industrial and developing countries. Major markets for the IC-engine generator sets are seen in the LDCs. Indeed, in Brazil and the Philippines, indigenous manufacture is already underway.

Production of syngas (CO/H₂ mixture) from biomass has not yet been commercialized; however, major pilot-plant or demonstration activity is underway in several countries. The primary energy application of syngas would be in methanol production for vehicular use. Nonenergy applications would be in ammonia and fertilizer synthesis. For countries having little or no natural gas or oil, a wood/peat-to-methanol option would have to compete with imported coal.

Direct liquefaction of biomass had its genesis in coal liquefaction. Work under the auspices of IEA's Forestry Energy Agreement (FEA) Group 'D' has spurred the development of process concepts that recognize the intrinsic differences between biomass and coal. This collaboration, known as the Biomass Liquefaction Test Facility (BLTF) project, is currently underway and may lead to the construction of a multipurpose international liquefaction test facility.

Anaerobic digestion technology is nearing commercial application in the food-processing industries and in large-scale farm operations. In general, the applications are cost effective when there is a demand for the product gas over most of the year and a credit is taken for environmental improvement. The smaller farm application still has to reach commercial viability. There is at present a major research effort in all aspects of methanogenesis and significant process improvements remain to be made.

Ethanol production in Brazil (from sugarcane) and the USA (from corn, i.e., maize) is on a relatively large scale although in both instances a considerable subsidy is required to make the production commercially viable. The technical feasibility of using ethanol in the gasoline system is well demonstrated. Major research is being undertaken to make the process technology more energy- and cost-efficient and to expand the feedstock base out of foodstuffs with their occasional high opportunity costs due to market shortages of grains and sugar. In Brazil, for example, research into the use of cassava and of eucalyptus wood (plantation grown) is underway and, in the majority of OECD countries, there is very active research into lignocellulosic conversion (e.g., wood and straw). Other alcohols can be produced and the French program is seeking isobutanol/acetone products from the fermentation of Jerusalem artichoke tubers for cosolvent use in the methanol-additive fuels.

Other liquid-fuel substitutes from biomass include the use of oilseeds such as sunflower and rapeseed to generate diesel-oil additives and substitutes. Oilseeds are very costly in comparison with other biomass resources, nevertheless research and development (R&D) has shown that esterification of plant oils leads to very suitable diesel extenders. In the context of energy security, this is a valuable finding.

Commercial Availability and Current R&D

Table 1 is a summary identifying the status of bioenergy systems with respect to the current stage of commercial development. By disregarding the role of end-use systems, it is possible to arrange a matrix of biomass resources with the cultural, harvesting, and conversion systems and to identify for each intersection the current status of the technology. In some instances, such as the algal production systems, it is inappropriate to choose certain technologies, such as combustion, and these are indicated by NA.

Table 1. Commercial availability and technology status for bioenergy^a

Type	Production systems		Conversion systems											
	Resource		Thermochemical ^b					Biotechnology						
	Culture	Harvest	Comb	l jv	m jv	Syngas	Solid	CH ₄	EtOH	Other				
Forest														
Primary	****	****	****	****	****	****	****	****	****	****	****	****	****	****
Mill residues	****	****	****	****	****	****	****	****	****	****	****	****	****	****
Forest residues	****	****	****	****	****	****	****	****	****	****	****	****	****	****
Short rotation forestry	***	**	****	****	****	****	****	****	****	****	****	****	****	****
Agriculture														
Sugar	****	****	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Crops	****	****	****	NA	NA	NA	**	**	****	****	****	****	****	****
Grains	****	****	NA	NA	NA	NA	NA	NA	****	****	****	****	****	****
Starches	****	****	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Oilseeds	****	****	****	****	****	****	****	****	****	****	****	****	****	****
Straw	****	****	****	****	****	*	*	*	****	****	****	****	****	****
Crop residues	****	****	**	**	NA	NA	**	**	****	****	****	****	****	****
Manure	****	****	**	**	NA	NA	**	**	****	****	****	****	****	****
Mariculture														
Fresh water	**	**	NA	NA	NA	NA	*	*	****	****	****	****	****	****
Marine	**	**	NA	NA	NA	NA	*	*	****	****	****	****	****	****
Algae	**	**	NA	NA	NA	NA	*	*	****	****	****	****	****	****
Other														
Peat	NA	****	****	****	****	****	****	****	****	****	****	****	****	****
Reeds	**	**	****	****	****	****	****	****	****	****	****	****	****	****

a ****, Commercial; ***, Demonstrated; **, Pilot-plant or experiment; *, Basic R&D; and NA not applicable.

b Comb = combustion; l jv = low joule value; and m jv = medium joule value.

In the case of peat, the mining technology (harvest) is highly advanced in countries where the climate permits a reasonable length of the solar- or wind-drying season. In other climates, where wet mining and dewatering will be necessary, the current technology status is at best at the pilot stage. Blanks in the table indicate that work might be undertaken but that I do not know the current status of such research.

A broad conclusion from Table 1 is that the production systems for biomass are generally mature and that, for dry feedstocks, combustion technology is commercially available. The area of greatest expansion and potential is in the biotechnology arena where, with the exception of alcohol production from traditional feedstocks such as sugar and starch, most systems are still in development.

Economic evaluation of bioenergy systems

Before going too far with the discussion of net energy balance, I should note carefully that the governing rules really are those of economics, not of energy balance, because by necessity any energy-conversion process, e.g., generation of electricity from coal or refining of gasoline from crude petroleum, reduces the total energy that is eventually available to the consumer. This is of course accepted. Thus, a coal-fired plant is normally only about 33% efficient (first law basis) in converting the heat in coal into a more useful form of energy -- electricity. Thus, for biomass as a whole, one has to ask the more specific question, "Does the production of energy from biomass achieve a net gain in a more desirable form of energy?" It is accepted that our society is running out of oil rather than out of energy and that the problem that faces us is that of replacing the high-grade uses of oil by alternative fuels, be they biomass- or nuclear-generated electricity. Thus, the focus will be on the liquid-fuel replacement characteristics of biomass.

An illustration of the constraints imposed by economics rather than energy can be seen in the case of woodchip transportation.

An 18-wheel truck with a capacity of about 88 m³ could accommodate almost 27 t of green wood chips at a chip density of around 320 kg/m³. These translate to 13.5 t oven dry (ODt) that could in principle, and probably in practice, be transformed into about 6 t or 8000 L of methanol. The fuel efficiency of the truck is about 0.04 L/t per km (litre of diesel equivalent) or 0.90 L/km for the fully loaded rig. If one assumes that, when methanol engines are available, methanol and diesel will be volumetrically equivalent in use, then the range of the truck driven by the methanol generated from the load would be in the neighbourhood of 600-900 km. The economics of a \$0.08-0.16/t per km charge will result in the transport cost being \$100-400/ODt for such distances and these are the reasons why hauls of up to 100 km are often considered to be limiting.

Figure 1 is an illustration of the simple model used to determine the net energy balance of biomass production. Starting with the conversion plant processing P ODt/day of biomass, this is converted with a direct oil-equivalent energy efficiency of $\theta\lambda$ where θ is the energy output (in GJ/t) and λ is an energy equivalence term with oil, e.g., ethanol in blends might replace 1.4 energy equivalent of oil product. Alternatively, burning green fuel in a boiler might derate the boiler from previous high-70% efficiency on natural gas down to low-60% resulting in a λ of 0.8. The gross oil equivalence of the process, however, has to have subtracted from it the fossil fuel that might be used in the conversion process, the energy required to transport and collect the biomass, the energy consumption of carrying the energy product to some market, the harvest energy requirements, and the silvicultural and agronomic inputs such as tillage and fertilizer.

Energy-balance calculations are very suspect -- particularly if they do not lay out all of the assumptions and particularly the boundaries on which the analysis is drawn. For example, the energy costs of harvest might include only the liquid fuels used in the process of harvesting or might also include embodied energy such as that required to make the steel used in the construction of the saws, tractors, and so on. If one were absolutely rigorous, the machine

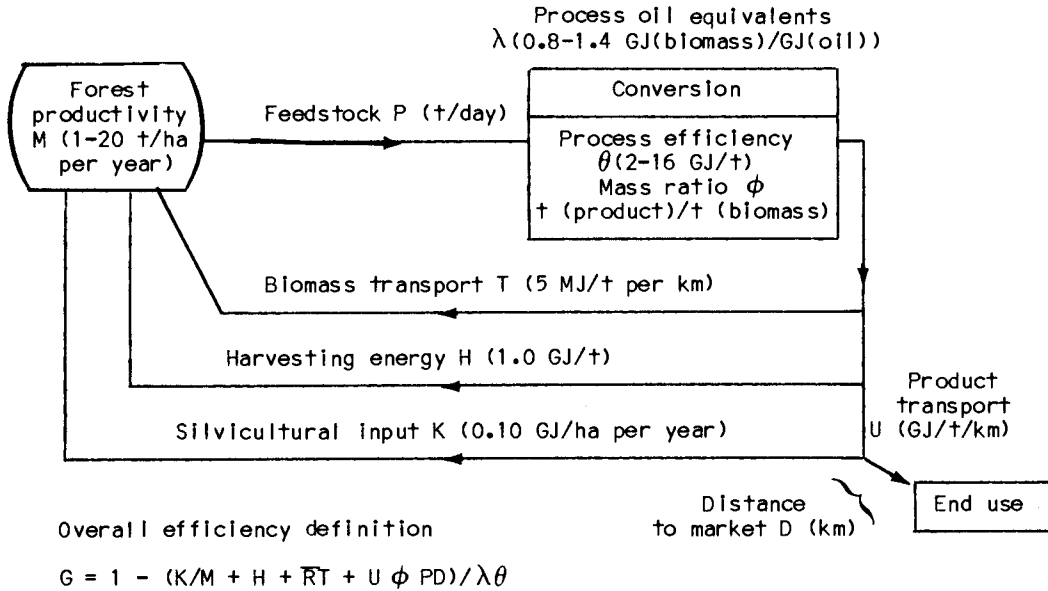


Fig. 1. Energy balance model.

operator's food intake might even be included as an energy input. The use of direct liquid-fuel equivalents and not embodied energy is arbitrary but justified here on the basis that these are, in the main, the dominant quantities.

It is assumed that harvest operations in general would be conducted on areas of 50-200 ha and that the energy cost of assembly to a landing would be included in the harvest-energy term. The energy costs of collection from landings to the plant site will be a function of the plant feedstock required and the biomass productivity. Many of the studies that address this assume either a real-life situation for which the roads are known, or alternatively, posit a simple geometrical model based on a production plant that is situated in the middle of a circular collection area. Real life is really not so convenient and the simple geometric model used in the estimates of transport work assumes that the plant is located at the point of a circle sector. For the purpose of this discussion, the number of sectors required to make up a circular geometry are used, for example, $n = 2$ is a semicircular geometry with the plant located on the midpoint of the diameter. All this terrain cannot be harvested because lakes, roads, townships, and recreation areas are not available for production and the simple model assumes that the area has a stocking density of ϕ harvestable land. These two parameters are used in a geometric index that ranges in value from 1 for a circular geometry when 100% of the area is harvestable to something of the order of 60 for a thin slice of one sector out of 12 that would make up the circle with a harvestable area of only 5% of the total area. The area harvested is P/M where P is the plant scale multiplied by the number of days of the year the plant is running and M is the biomass productivity.

The average haul distance to the conversion plant is:

$$\bar{R} = 0.6833(\tau)(n/\phi)^{0.5} (P/M)^{0.5}$$

where τ is a tortuosity factor relating distance traveled to the straight line distance between the harvest area and the process plant;

0.6883 is a factor that rationalizes the units of the various terms so as to arrive at distance in kilometres and thus the average energy cost per delivered tonne of biomass will be \bar{R} (Overend 1982: 75-86); and

T is the energy cost/tonne per kilometre for transporting biomass.

The feedback model described in Fig. 1 can be formulated as follows:

$$G = 1 - (1/\phi\lambda) [K/M + \overline{RT} + (S + H + U\phi PD)]$$

- where: G = (net energy)/(gross conversion-plant output);
 K/M = (agronomic/silvicultural input)/tonne biomass;
 \overline{RT} = transport energy/tonne;
 K = agronomic/silvicultural energy equivalent;
 M = biomass productivity (ODt/ha per year);
 S = process-energy requirement/tonne;
 H = harvest-energy requirement/tonne;
 D = distance from process plant to market (km);
 ϕ = mass conversion factor, product/tonne; and
 U = transport-energy cost for product transport.

The algorithm for calculating G is not difficult to program and the majority of the parameters required are available from the literature sources given in the reference list: Pimental (1980) is a particularly useful source of data.

The conventions to describe the energy efficiency of biomass systems are not yet fixed. The treatment of the feedback loop given above is comparable to the method used by Weisz and Marshall (1979) who used the ratio of net fuel productivity to gross output as their energy efficiency indicator. The TRW (1980) study chose to identify the fuel investments and the energy gain for various ethanol-production systems with the product displacing gasoline with values running from 1 to 2. Conversion of the TRW data to G factors as used here is obtained through the relationship

$$G/(1 - G) = (\text{net energy gain})/(\text{input energy})$$

on the basis that the biomass, i.e., solar-energy input, is "free" and not counted as an input-energy term.

Table 2 is calculated from the data of tables 6-1 and 6-2 of the TRW report assuming that gasohol is volumetrically equivalent to leaded gasoline (TRW Case b).

Separate calculations through the feedback model give essentially the same overall efficiency factor G for corn processes. However, by breaking out the individual parameters, a number of topical concerns in R&D can be treated through assumed or measured variables to evaluate management strategies such as intensive versus extensive forestry.

For example, the use of energy-intensive nitrogen fertilizer to increase the biomass productivity M appears, on an energy basis, to be compensated for by the reduction in hauling distance for a corn-ethanol plant (Fig. 2). In this instance, a production curve of corn for a given fertilizer input was used (Fluck and Baird 1980: 90-93) and it was assumed that the natural gas that went into making fertilizer would have been able to displace an equal quantity of liquid fuel on an energy-content basis. The apparent trade-off comes because, in this case, the term K/M increases only slowly while \overline{R} is reduced.

Table 2. Gain factors for ethanol production

Process cycle	Premium fuel input (MJ/L ethanol)	Net premium fuel gain (MJ/L ethanol)	G
Corn feedstock			
Using coal	10.31	32.05	0.76
residues	20.82	20.10	0.49
gas	21.99	18.92	0.46
Cellulose			
Electricity	1.31	37.79	0.97

Source: TRW (1980), tables 6-1 and 6-2.

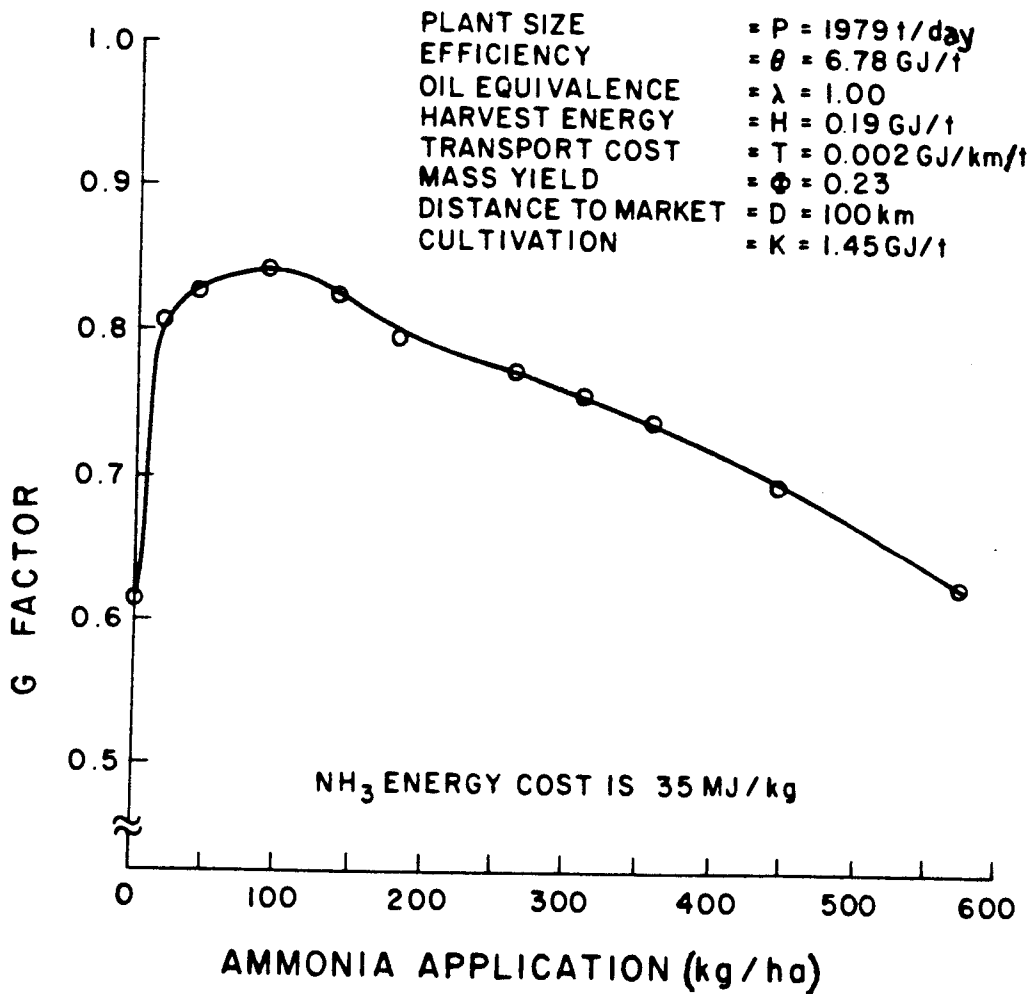


Fig. 2. Corn to ethanol (stover fuel).

Table 3. Influence of conversion-plant efficiency factors on the total energy balance

Process	Capital cost (\$/GJ)	GJ/t	G	Net-energy yield (GJ/ha)
Pelletizing and combustion	2.0	15	0.87	26
Medium-joule-value gas	5.0	10	0.80	16
Methanol (low-efficiency process)	20.0	6	0.60	7.2

A more rational evaluation would of course examine economic trade-offs between more efficient, but capital-intensive, process plants and the reduction in land-acquisition costs and transport-cost elements. In the absence of economic indicators, the use of energy as a proxy is a useful guide. Table 3 compares the net-energy benefit of different conversion routes starting with native poplar in Saskatchewan at a sustainable yield of 2 ODt/ha per year.

When the capital cost of these technologies is examined along with the net-energy yield, the economic benefits of a simple preparation process followed by clean combustion evidently far outweigh trying to displace oil by entering the premium mobile-fuel market through alcohol-fuel production.

Economic Evaluation of Bioenergy Systems

As could be seen from the energy-balance model, the final cost of biomass fuel is a function of the capital cost, efficiency of the conversion plant, and the feedstock cost.

Feedstock costs are very dependent on the intensiveness of cultivation, which is a function of labour, fertilizer, irrigation, machinery, and crop protection costs as well as the cost of transport of the biomass to the processing plant. The costs to roadside of field crops or of wood can range from \$0-100/t depending on the intensity of operation. In Canada, straw and forest residues (branches and noncommercial trees) cost about \$20/t at the roadside.

The key to biomass cost usually lies in the transport cost -- from the field to the processing plant. Although some biomass is fairly dry and dense, as is the case for grains, the majority of residues are either extremely moist (e.g., green wood with 50% moisture) or extremely bulky and of low density. If the biomass is half water, then the cost of biomass fuel movement is accordingly doubled on a unit of energy basis. Crop residues such as straw and stover and chipped forms of wood all have extremely low packing densities. A low packing density causes the load carrier to "cube out" because the large volume of the residue means that the mass of the full load is less than the vehicle capacity. Typically, the threshold for "cube out" is 300-500 kg/m³ load density. Typical bulk densities are listed in Table 4.

The cost of moving biomass is a function of (Loading + Unloading Time) x Equipment Cost and of Transit Time x Hourly Cost on the basis of 1 t carried. Fuel, labour, capital cost, and rates of return vary in different countries as do the equipment specifications. Over a 100-km radius, grain movement in Canada costs about \$0.08/t per km. Wood movement incurs slightly higher costs of 0.10/t per km. Because of the fixed costs for loading and unloading, shorter radii are more expensive. A rule of thumb in North America is that loading and unloading each cost about \$3-5/t.

Table 4. Bulk density of biomass resources

Biomass material	Bulk density (kg/m ³)
Grains	
Wheat	772
Corn	721
Barley	618
Rice	579
Bulk wood	
Dry	400-800
Wet	400-1600
Spruce chips	
Wet	400
Dry	200
Straw or stover	120
High density bale	240

Typically, grain costs at a factory gate are \$100/t whereas lignocellulosic residues such as straw and stover or wood can be delivered for \$30/t. With these costs in mind, the capital costs of the various technologies can be integrated and compared with those of the oil-equivalent costs because oil displacement is the primary role of biomass energy forms.

In evaluating the potential of technology to satisfy the given end-use needs, it is important to have a yardstick against which the current state of development of the technology can be measured. For the purpose of this discussion, the many stages of technology development are simplified to four: Research and Development, Engineering Development, Demonstration, and First Commercial Plant.

Each of these phases of development has different characteristics with regard to intensity of effort in terms of dollars spent. By definition, the R&D phase is relatively low cost and involves the risk of the concept not working out due to technical reasons. By the engineering development phase, the problem of technical feasibility is replaced by the challenges of materials and production and control problems. It is usually in this phase that the first credible estimate of the economics of a process can be made. Generally, if the economic outlook for both the process and product is promising, the next phase of development, the demonstration, is initiated. At this point, the real-life political and social problems of introducing new technology can be evaluated. Providing that the demonstration goes well, the demonstration will lead to the commercialization of the technology.

Figure 3 illustrates the technology development cycle with a time scale and rate-of-investment scale superimposed using the example of the advent of nuclear energy as a commercial technology (data and concept derived in part from the work of Hill, 1978). It must be recognized that this simplified picture is a 20:20 hindsight view of technological development and that, for each commercial technology, there are at least 10 demonstration projects, possibly 100 engineering development projects, and 1000 R&D projects.

The current state of development of biomass conversion technology is probably the hardest variable to fix (along with capital cost) and I have taken the following as criteria:

- Commercial technology: One or more full-scale plants have been constructed;

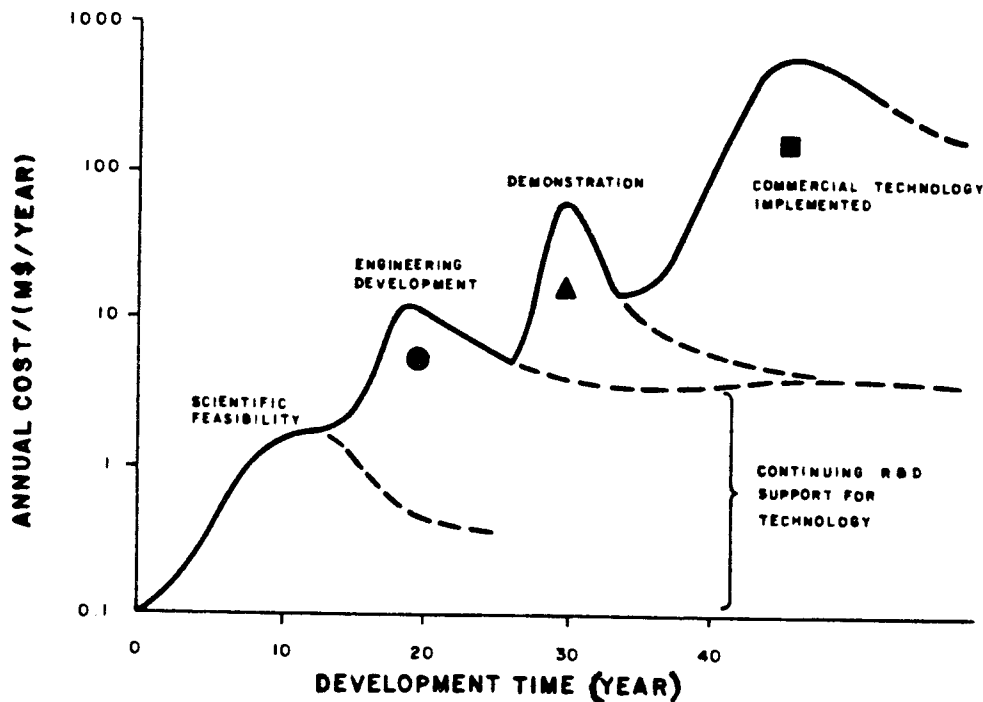


Fig. 3 Time scale for energy technology to reach commercial status.

- Demonstration: An innovative process currently existing at more than 25 ODt/day input;
- Engineering development: A process development unit or pilot plant usually around 1 ODt/day; and
- Research and development: Essentially small-scale laboratory work at a scale of grams per hour.

Figures 4 and 5 are simple maps to illustrate the capital intensiveness of biomass-conversion systems on the Y axis and, by using the reciprocal of process efficiency, it is possible to show the resource impacts on the X axis.

Ideally, the comparison of different systems would be by means of the cost of the delivered-energy form. This, however, is almost impossible because feed-stock costs are often opportunity costs that are quite specific to the site and market envisaged for a process. Similarly, financing regimes (debt/equity ratios, taxation, and subsidy) affect the capital-cost contribution to the product price as do local wage rates.

Each capital cost and efficiency graph has five curves to illustrate lines of equal product cost where the following formula and assumptions are used:

$$\text{Product cost (\$/GJ)} = (100F/20\eta) + [D(CRF + M)]/(66\eta)$$

where: F = feedstock (wood) cost (\$ per ODt);

20 = HHV of wood, i.e., 20 GJ/ODt;

66 = factor derived from number of days (330) in year combined with the HHV of wood;

η = efficiency of conversion (%) defined as the fraction (HHV product/HHV of feedstock);

CRF = capital recovery factor ($A/P_{i,n}$) expressed as a fraction;

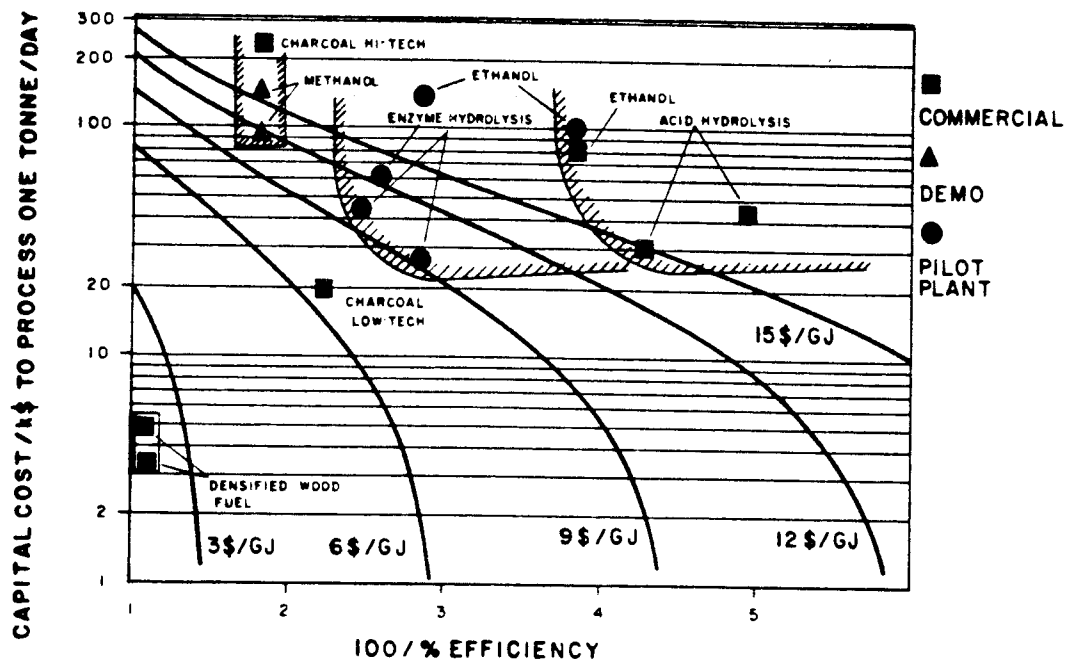


Fig. 4. Bioenergy systems capital cost and efficiency.

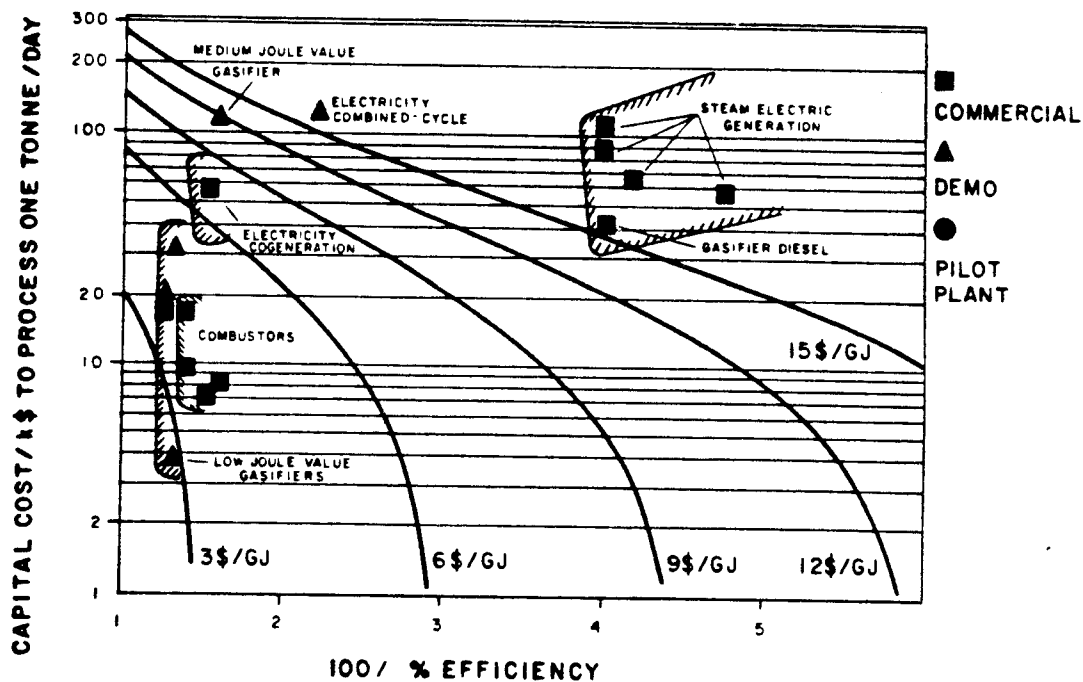


Fig. 5. Bioenergy systems capital cost and efficiency.

M = operating and maintenance (O&M) costs expressed as a fraction of capital investment; and

D = capital cost to process 1 ODt/day of feedstock.

This, albeit simplified, costing procedure when used with fixed-product costs of \$3-15/GJ enabled the variation in capital cost with efficiency to be evaluated for the following parameters:

Feedstock cost	= F	= \$40/ODt (or \$2/GJ)
Plant life cycle	= n	= 20 years
Discount factor	= i	= 15% per year
CRF	= $A/P_{i,n}$	= 0.15976
O&M cost factor	= M	= 0.15

Examination of a large volume of cost data in the open literature enables what can only be generalizations to be made for areas of technology. In general, costs were obtained in 1981 dollars by use of the consumer price index (CPI) and are defined as being exclusive of land and services (i.e., within battery limits). In most instances, buildings and on-site services, contingencies, interest during construction, and working capital can increase the quoted costs by 50-100%.

Although quoting cost per daily tonne processed may be unfamiliar to most, it is in fact a convenient yardstick. To illustrate a typical well known example, the equivalent cost for electricity generation is often quoted as being about \$1000/kW capacity.

One kilowatt generated for 24 hours would result in an electricity output of 24 kWh or 86.4 MJ/day. If wood is combusted, steam generated, and electricity produced at an efficiency of 25% then 346 MJ of wood energy will be required. Because 1 t (anhydrous) has 20 GJ of energy, then \$1000 invested will process:

$$\text{Wood processed}/\$1000 \text{ invested} = (346 \text{ MJ/day})/(20 \text{ GJ/t}) = 0.0173 \text{ ODt/day}$$

Thus the capital cost of electricity generation from wood at 25% thermal efficiency, using the \$1/W rule of thumb, requires about \$58000/t per day.

Examination of the electricity-generation points (Fig. 4) shows how thermal steam-condensing technology requires very high opportunity costs for the produced electricity of more than 55 mills/kWh. In Canada, long-run marginal costs of hydro, nuclear, and coal generation are likely to be less than 30 mills/kWh and thus is a barrier to this utilization of wood.

The profitability of direct combustion and the near-commercial gasification technologies is also evidenced by their high efficiencies and location between the \$3/GJ and \$6/GJ curves, which makes both competitive with oil and natural gas in the USA.

Cogenerated electricity, although having similar or greater capital costs than condensing-steam generation, has, by virtue of the high efficiency factor, a very competitive edge against purchased electricity in pulp and paper mills.

Figure 4 is a very similar treatment for liquid- and solid-fuel production. The only liquid fuel from wood production that can be classed as commercial is in fact the updated World War II-vintage Scholler/dilute-acid hydrolysis. As can be seen, the high capital cost and limiting efficiency of 25% create a large obstacle to commercial implementation. Enzymatic processes, although experimental, offer similar capital costs but, with the higher inherent efficiency, will prove to be more competitive in the long run. Methanol from wood is already at the demonstration stage of development and is likely to be capable of competing with methanol derived from fossil fuel in certain regions.

Solid fuels include densified wood and charcoal. Densification offers extremely high efficiency and the lowest capital cost per unit processed. The downstream utilization of the densified fuels does, however, await the appropriate combustion and gasification equipment in the marketplace.

Charcoal production can require extremely high technology with capital costs greater than those for methanol production when maximum heat and by-product recovery are attempted. It can also be extremely "low tech" requiring almost no investment when the admittedly inefficient earth-covered kilns are constructed in the forest. The Brazilian production of metallurgical coke is mainly in brick-built kilns, which are held to be the most economical for a minimum capital investment without by-product recovery.

Discussion

As I have shown, an extremely large range of technologies is available for biomass conversion, and the available systems cover a large range of scales and technical maturities. Energy balance and economics favour the direct combustion of biomass for process heat and space-conditioning applications. Where the local demand requires conversion to electricity or liquid fuels, the energy and economic penalties are severe and are a barrier to implementation.

In-house research at NRC is looking at the contribution that R&D might make to improving the biotechnology-based conversions. We have a computer simulation model that incorporates the several unit processes involved in converting wood to ethanol. The basic model is derived from the Madison process, which is still in use in the USSR and is marketed by Swiss and New Zealand companies. Our research program is looking at the role that modern technologies, such as advanced anaerobic digestion or membrane separations, will play in reducing the final cost. Table 5 shows some typical results for the capital and energy costs of two different process options.

Table 5. Steam explosion plus lignin extraction process versus standard Madison process with anaerobic digestion

Unit operation	Capital cost		Energy cost	
	(k\$US)	%	(US\$/hr)	%
Steam explosion	460	8.7	112	29.2
Chemical extraction	270	5.1	10	2.6
Hydrolysis	50 (760)	0.9 (12.8)	90 (354)	23.0 (53.1)
Neutralization	130 (600)	2.5 (10.1)	0 (0)	0 (0)
Sugar concentration	110 (290)	2.1 (4.9)	53 (192)	13.8 (28.8)
Fermentation	1220 (1230)	23.0 (20.8)	48 (72)	12.5 (7.3)
Distillation	730 (740)	13.8 (12.5)	71 (72)	18.5 (10.8)
Anaerobic digestion	2336 (2298)	44.0 (38.8)	0.2(0.1)	- (-)
Total	5306 (5918)	100 (100)	384 (667)	100 (100)

Production Rate: 1370 L/hour (1402 L/hour)
 Overall Yield: 164.5 L/t dry wood (168.3 L/t dry wood)
 Selling Price: US\$0.93/L (US\$0.92/L)

Note: Values in brackets are for standard Madison process.

Our observations and conclusions are:

- In such a multistep process, it is not sufficient to improve only one step in the sequence.
- The processes are likely to be economic only under circumstances where there can be significant by-product (I prefer the term "coproduct"!) opportunities. Examples are single-cell protein (SCP) from the xylose stream, dried distillers grains, adhesives, and polymers from the lignins.
- Our findings are similar to those of a study conducted under the auspices of the EEC FAST (Forecasting and Assessment in the field of Science and Technology) program; see, for example, Atkinson and Sainter (1982). The major problems facing the present and future biotechnology industries are the downstream processing steps in which products and reactants have to be separated and purified before use. A major concern in the wood-to-ethanol process has to be the immense volume of effluent that must be treated. The examples above include advanced anaerobic digestion before secondary treatment and this constitutes one of the lower-cost options that we have modeled. Even so, the effluent cleanup is close to 40% of the capital investment.
- The modeling exercise has also raised doubts on the viability of small-scale operations than can afford less integration of energy and chemical flows than we have incorporated. In fact, the US gasohol program illustrates this problem: Alcohol Week (Anon. 1983: 3) notes the problems that the small, less than 2×10^6 US gallons/year, producers have. Low initial costs have led to high equipment replacement and operating costs, the corn feedstock is more expensive in small quantities and the alcohol yields obtained are less than those of the large plants. Major technical problems have been found with waste treatment and the evaporative and energy-recovery systems.

Although it is possible to discuss technical fixes for the liquid-fuels option, it is still necessary to consider the economic and social issues in introducing this technology. Both in the OECD and LDC countries, the alcohol fuels are not entirely compatible with the gasoline system and the Brazilian experience shows that major institutional changes take a long time to be successfully implemented.

Even in a subject as superficially simple as the cookstove in LDCs, this is the case. For a long time, the firewood crisis has been looked at as a technical-fix issue, particularly in the area of stove technology. Recent evaluations have highlighted that it is not possible to say with certainty that fuelwood savings are being achieved. In many instances, this is because the technological improvements that are dictated by the need for efficient combustion remove some of the functions of the open and semi-open fires traditionally used for cooking.

References

- Anonymous. 1983. Alcohol Week, July 13.
- Atkinson, B. and Sainter, P. 1982. Development of downstream processing. *Journal of Chemical Technology and Biotechnology*, 32, 100-108.
- Fluck, R.C. and Baird, C.D. 1980. *Agricultural energetics*. AVI Publishing Company Inc., Westport, CT, USA.
- Hill, G.R. 1978. Critical paths to coal utilization. *International Journal of Energy Research*, 1, 342-349.

- Overend, R.P. 1982. The average haul distance and transportation work factors for biomass delivered to a central plant. In Biomass 2. Applied Science Publishers, Barking, U.K.
- Pimental, D., ed. 1980. Handbook of energy utilization in agriculture. CRC Press Inc., Boca Raton, FL, USA.
- TRW (Energy Systems Planning Division). 1980. Energy balances in the production end-use of alcohol derived from biomass. U.S. National Alcohol Fuels Commission, Washington, DC, USA.
- Weisz, P.B. and Marshall, J.F. 1979. High-grade fuels from biomass farming: potentials and constraints. Science, 206, 24-29.

Appendix: Definitions

Biomass: Vegetable matter produced by means of photosynthesis.

Bioenergy: The use of biomass as a fuel or as a feedstock for energy conversion.

Biotechnology: The application of scientific and engineering principles to the processing of materials by biological agents to provide goods and services. Unlike thermochemical conversion, the biological agents require relatively pure or homogeneous substrates having well defined chemical composition and structure.

Municipal solid waste (MSW): The energy content of which is mainly derived from biomass sources, e.g., cellulose from paper.

Peat: Decayed vegetable matter undergoing conversion to fossil fuel especially to coal. Technically, peat is a nonrenewable energy source.

Thermochemical conversion: Processes such as combustion, pyrolysis, and gasification in which the transformation of the carbon (C), hydrogen (H), and oxygen (O) in the biomass is effected by the application of heat. In general, the final products are only a function of the initial C, H, and O composition, the pressure, and the temperature.

**LIQUID FUELS FROM RENEWABLE RESOURCES:
TECHNOECONOMIC COMPARISONS OF
ALTERNATIVE FEEDSTOCK USES**

M. Moo-Young, C.W. Robinson, and Robert Lencki*

Recent recognition that petroleum-based fuel and chemical feedstocks are becoming increasingly scarce has encouraged research aimed at developing alternatives based on renewable raw materials. Lignocellulosics (especially forestry, agricultural, and other industrial residues) are of prime interest. Various conversion scenarios have been proposed that employ chemical, physical, or biochemical routes to produce a variety of gaseous, liquid, and solid products. This review examines the potential base-line economics of these processes to try to identify the techno-economic "bottlenecks": the biochemical routes to energy from renewable biomass resources are of primary concern.

Raw Material Costs

The main attraction of lignocellulosics is their comparatively low cost (\$0-50/t) compared to more conventional raw materials such as corn (\$120/t) or molasses (\$200/t). A further benefit of using some biomass residues such as agricultural manure or industrial pulp sludge is abatement of environmental pollution (with a concurrent net negative cost for the feedstocks). Table 1 lists the related production costs when molasses is transformed into a number of fermentation products (Kovaly 1982). The need for cheaper raw materials such as lignocellulosics is indicated.

In the USA, the acetone/butanol/ethanol and lactic acid fermentations are currently not competitive with synthetic chemical routes but ethanol via fermentation, a process that was rapidly replaced by synthesis from ethylene after World War II, has recently witnessed a resurrection. Annual sales of ethanol increased to 795×10^6 L in 1982 from 280×10^6 L in 1981, almost all of this increase being produced from corn (Haggin and Krieger 1983). This particular grain is used instead of molasses because it is produced in large quantities in the U.S. and the starch that it contains is easily converted to fermentable sugars.

Table 1. Percentage of production cost related to molasses feedstock for various fermentation products

Fermentation product	Molasses as % of production cost
Ethanol	68
Acetone/butanol/ethanol	55
Calcium gluconate	46
Itaconic acid	43
Citric acid	24
Lactic acid	15

*Department of Chemical Engineering, University of Waterloo, Waterloo, Canada

Considerable research has gone into improving the various ethanol fermentation unit operations. For example, our laboratory has developed a reactor utilizing yeast cells immobilized on wood chips that can significantly reduce fermentation costs (Robinson et al. 1981). The advantage of this immobilized cell reactor (ICR) can be seen in Table 2, which shows an economic comparison among the ICR, a conventional continuous stirred-tank fermentor (CSTF), and a CSTF with cell recycle. The advantage of the ICR arises from the high throughput and higher ethanol concentration in the fermentor broth. Other work has focused on developing ethanol separation techniques that are more economical and energy efficient than current distillation methods (Lencki et al. 1983). These innovations will significantly improve the economics of producing ethanol from corn or other feedstocks. However, as indicated in Table 3, recent economic analyses of corn-based ethanol plants (Katzen et al. 1979; Kitchen and Tong 1982; Keim 1983) have had similar conclusions to that observed with molasses: an inexpensive source of fermentable sugar would have a significant effect on the economics of fermentation ethanol.

Table 2. Cost comparison of various ethanol fermentor designs^a

Cost parameter	ICR	CSTF	CSTF with recycle
Total Investment (10 ⁶ US\$)	12.0	24.1	19.9
Payout time (years)	2.2	4.5	3.3
Return on Investment	45.2	21.3	30.2

^a 10⁶ US gallons/year ethanol, 330 days/year operation, sugar costs the same for all cases.

Table 3. Percentage estimates of total operating cost for ethanol-from-corn production

Parameter	Stone and Webster ^a	Raphael Katzen Associates ^b	Consultants Inc. ^c
Raw materials			
Corn	70.5	70.0	62.7
Miscellaneous	6.9	1.0	4.5
Fuel			
Gas	1.4	-	5.6
Coal	-	3.8	-
Electricity and water	0.4	2.4	2.3
Labour	2.9	5.7	4.0
Depreciation	8.9	4.5	12.4
Taxes and insurance	1.1	1.4	2.3
Miscellaneous overhead	4.8	8.3	1.1
Maintenance	4.2	2.9	5.1
Total operating cost	100.0	100.0	100.0

^a Based on 1981 production of 30,000 t/year.

^b Based on 1978 production of 150,000 t/year.

^c Based on 1983 production of 30,000 t/year.

Lignocellulosics -- A Cheaper Sugar Source?

Because corn surpluses and the resulting tax incentives in the U.S. may not exist elsewhere and because diversion of grain to fuel production also raises the "food versus fuel" argument, waste lignocellulosics appear to offer an attractive alternative. For example, Canada produces about $140 \times 10^6 \text{ m}^3$ of wood residues and by-products per year (Phillips et al. 1979). Lignocellulosics, if economically hydrolyzed and fractionated into its components (glucose from cellulose, xylose and other sugars from hemicellulose, and phenolics from the lignin fraction) may provide inexpensive feedstocks for fuel and chemical production.

Unfortunately, because of the crystalline structure of cellulose and the presence of lignin, lignocellulosic materials are more difficult to use as fermentation media than starch. Thus, a pretreatment method must be found. Figure 1 summarizes many of the proposed pretreatment schemes now under development.

An economic analysis for ethanol production from wood, corn stover, and straw using the enzymatic or acid hydrolysis pretreatment methods has recently been conducted (Stone 1982). With a current ethanol selling price of \$0.45/L, the results indicate that, with acid hydrolysis, only the New Zealand scenario appears to be economic (Table 4). However, the processing cost estimate for this system seems unreasonable. Most estimates for systems based on enzymatic hydrolysis pretreatment (Table 5) appear to be uneconomic, but by assuming high

Table 4. Various cost estimates for ethanol production from wood based on acid-hydrolysis pretreatment

Parameter	New Zealand	Nolan (Univ. Penn.)	Katzen	Mitre Corp.	American Can Co.
Year estimate made	1979	1980	1975	1977	1980
Plant size (ODt/day)	1000	1364	1364	1545	1818
EtoH production (10^6 L/year)	99.5	94.6	94.6	105	75.7
% Yield (EtoH/wood, weight basis)	23.8	16.9	16.9	16.3	10.0
Capital cost (10^6 US\$)	39.5	93.7	68.4	212	55.6
Capital cost/L (US\$)	131	327	238	667	242
Production costs (10^6 US\$/year)					
Substrate ^a	10.6	14.3	14.5	16.4	19.3
Fixed and variable	3.8	16.1	9.5	37.1	25.6
Capital	11.8	28.1	20.5	63.7	16.9
Total	26.2	58.5	44.5	117.3	61.7
Production cost of EtoH (US\$/L)	0.27	0.62	0.47	1.12	0.81
Production cost after by-product allowance (US\$/L)	0.22	-	-	-	0.68

Source: Stone (1982).

^a At US\$32.2/t wood.

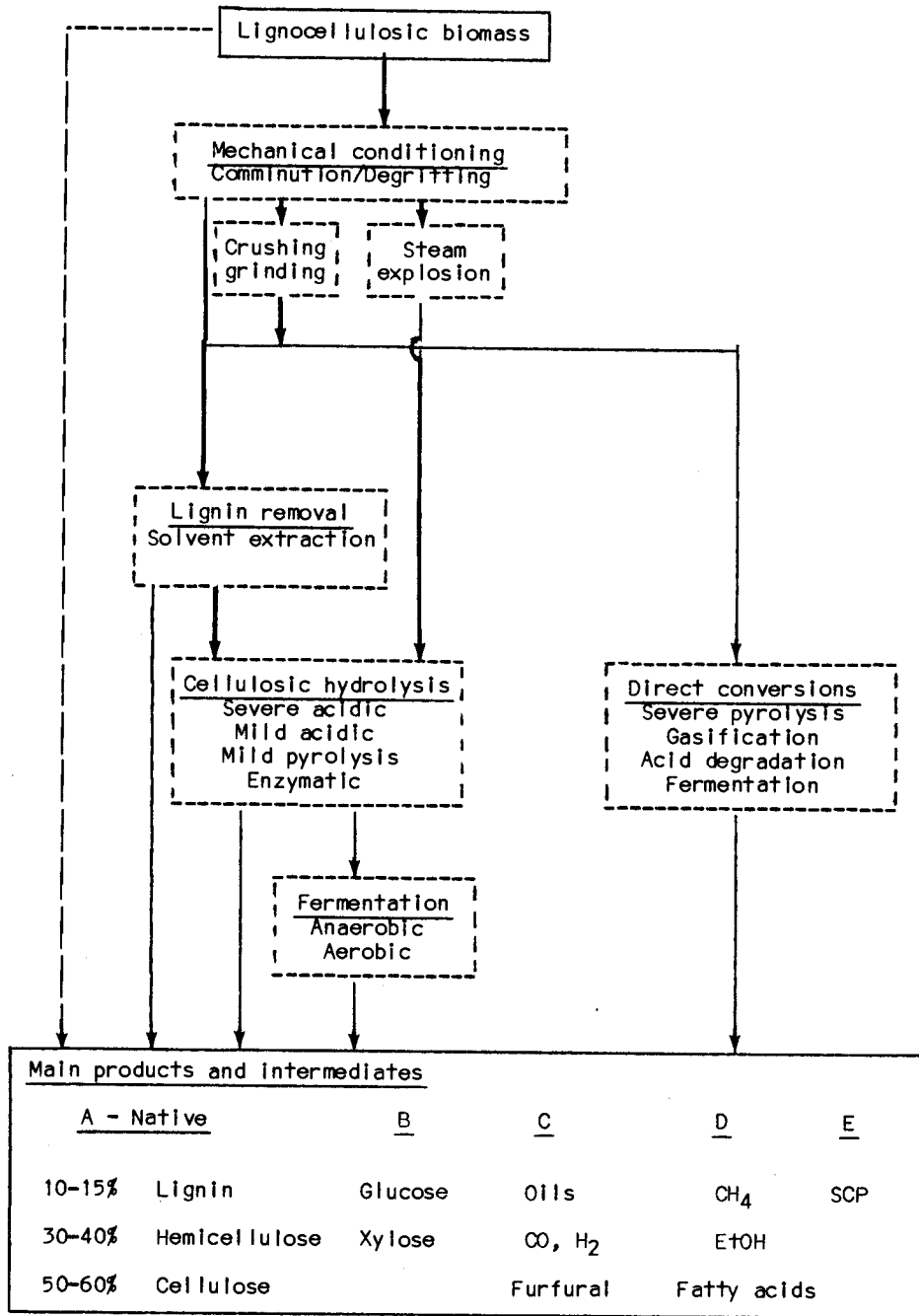


Fig. 1. Outline of various lignocellulosic pretreatment/conversion strategies.

by-product credits (a possibility with these processes), these could be feasible. For example, in the case of the lotech process, a large by-product credit of \$0.28/L of ethanol has been assumed.

Table 5. Various cost estimates for ethanol production from lignocellulosics based on enzymatic-hydrolysis pretreatment

Parameter	Iotech	Univ. Penn.-GE	Emert Katzen	Univ. Cal. (Wilke-SRI)		MIT	Univ. Penn. (Nolan)
				I	II		
Year of estimate	1980	1980	1979	1978	1978	1979	1980
Substrate	Wood	Wood	Wood	Wheat straw	Corn stover	Corn stover	Corn stover
Plant size (OD+/day)	227	1700	1818	2970	1250	1363	1559
EtOH production (10 ⁶ L/year)	22.0	94.6	189.2	94.6	39.4	104.1	189.2
% Yield(EtOH/wood, weight basis)	23.1	13.3	24.6	7.6	7.5	18.3	29.3
Capital cost (10 ⁶ US\$)	22.9	64.0	112.2	120.7	29.4	34.3	75.8
Capital cost/L (US\$)	344	224	196	422	247	109	133
Capital cost/tonne feed (10 ³ US\$)	101	37.7	61.7	40.7	23.5	25.2	48.6
Production costs (10 ⁶ US\$/year)							
Substrate ^a	2.5	18.5	19.8	32.4	13.6	14.8	51.6
Fixed and variable	4.1	19.7	29.5	21.0	11.9	9.7	26.5
Capital	6.9	19.2	33.7	36.3	8.8	10.3	22.7
Total	13.5	57.4	83.0	89.7	34.3	34.8	100.8
Production cost of EtOH (US\$/L)	0.61	0.60	0.44	0.95	0.88	0.33	0.54
Production cost after by-product allowance (US\$/L)	0.33	0.55	0.33	-	0.82	0.31	-

Source: Stone (1982).

^a At US\$32.2/t of wood.

Competitive Process Options

Other biomass conversion options should be examined. A comparative appraisal of these processes was conducted by the Stanford Research Institute and is summarized in Table 6 (Schooley et al. 1978). Direct combustion is the most efficient means of energy conversion but this energy is best used at the point of production and no chemical products are derived. Catalytic liquefaction can produce a transportable liquid oil and oxygen gasification yields a synthetic natural gas that can be transported or converted to methanol.

Methanol is a useful chemical feedstock that can be used to produce formaldehyde (its current major use), olefins, ethylene glycol, vinyl acetate, acetic acid and anhydride, ethanol, and ethylbenzene-styrene from toluene (Sherwin 1981). Methanol used directly as a gasoline octane booster has phase separation and corrosion problems but this can be solved either by conversion to methyl-tert-butyl ether if excess isobutene is available or by modification of the generation process to create some higher alcohols that reduce these drawbacks.

Table 6. Estimated cost of fuels^a

Biomass	Product	Process	Size (10 ³ GJ/day)	US\$ per GJ	Process efficiency (%)
Wood	Oil	Catalytic liquefaction	32.3	5.09	53
Wood	Methanol	Gasification (O ₂)	34.8	7.36	58
Wood	SNG	Gasification (O ₂)	37.9	6.08	63
Wood	Steam (432°C)	Direct combustion	46.4	2.84	77
Wood	Electricity	Direct combustion	(150 MW)	15.53	21
Wood	Oil	Direct combustion and char	960	4.27	74
Wood	Electricity	Cogeneration and direct combustion	45.9	3.24	32
Wheat straw	Ethanol	Enzymic hydrolysis and fermentation	5.8	49.86	11
Sugar- cane	Ethanol	Fermentation	5.8	30.52	45
Algae	Ethanol	Acid-hydrolysis and fermentation	6.0	10.43	32

Source: Schooley et al. (1978).

^a Including tax (52%), interest (9%), and return on investment (15%) discount cash flow.

From the results of a recent study (Perez-Blanco and Hannon 1982), on a dollar per kilojoule or process efficiency basis, methanol seems to be a better choice than ethanol for use as a motor-fuel extender or as a starting point for producing many chemicals. For example, the provincial government of Ontario in Canada is now interested in the possible use of lignocellulosics to produce methanol (Mackay and Sutherland 1976).

Ethanol — How Attractive a Product?

If a lignocellulosic pretreatment/fermentation route is chosen, is ethanol the best product to be produced? To determine which scheme and product mix should be utilized to maximize the economics of such a process, more studies are required, especially at the pilot-plant scale. However, some insight can be obtained with estimates of the maximum possible revenue and processing costs of the various products. For example, it would be foolish to take cellulose pulp worth \$0.45/kg and turn it into glucose worth only \$0.07/kg (Worthy 1981).

The fermentation of glucose formed from cellulose can produce a large variety of products. If produced in conjunction with a hydrolysis plant, the volume of these products would have to be substantial to achieve maximum economy of scale. Table 7 lists some of the possible large-scale uses. Compared to ethanol, the acetone/butanol/ethanol and acetic acid fermentations do not seem attractive at equal or lower revenues and higher processing costs. Glycerol and citric acid may be economical because of their high value. Conversion of the sugar to a molasses-like syrup, single-cell protein (SCP), or high-fructose syrup may also be economically attractive.

Table 7. Possible uses of produced glucose

Process/ Organism	Products	Product yield (kg/kg glucose)	Product value (US\$/kg)	Maximum possible revenue (US\$/kg)	Product market size (10 ⁵ +/year)	Processing cost	Separation cost
<u>Saccharomyces cerevisiae</u>	Ethanol	0.49	0.62	0.302	791	Medium	Medium
<u>Clostridium acetobutylicum</u>	Butanol	0.18	0.75	0.135	1813	Medium	High
	Acetone	0.09	0.64	0.057	4773		
	Ethanol Total	0.03	0.62	0.019 0.211	791		
<u>Saccharomyces cerevisiae</u>	Glycerol	0.26	1.60	0.416	815	Medium	High
	Ethanol	0.17	0.62	0.105	791		
	Acetaldehyde Total	0.11	0.74	0.081 0.602	675		
<u>Clostridium thermoaceticum</u>	Acetic acid	0.60	0.51	0.304	5960	Medium	High
<u>Aspergillus niger</u>	Citric acid	0.70	1.56	1.09	518	High	High
Sugar concentration	Glucose syrup	1.00	0.22	0.22	Large	None	Medium
<u>Saccharomyces cerevisiae</u>	SCP	0.50	0.30	0.15	Very large	Medium	Medium
Glucose isomerase	HFCS	1.00	0.40	0.40	-	High	Low

Sources: Underkoffler and Hickey (1954); Anon. (1981, 1983).

Table 8. Possible uses of produced xylose

Process/ Organism	Products	Yield (kg/kg xylose)	Product value (US\$/kg)	Possible revenue (US\$/kg)	Product market size (10 ³ t/year)	Processing cost	Separation cost
<u>Clostridium acetobutylicum</u>	Butanol	0.18	0.75	0.135	1813	Medium	High
	Acetone	0.09	0.64	0.057	4773		
	Ethanol	0.03	0.62	0.019	791		
Glucose isomerase and <u>S. pombe</u>	Ethanol	0.45	0.62	0.28	791	Medium	Medium
	Ethanol	0.27	0.62	0.17	791	High	High
<u>Pachysolen tannophilus</u>	Xylitol	0.15	1.54	0.23	-		
<u>Aerobacter aerogenes</u>	Butandiol	0.35	0.68	0.24	(6709) ^a	Medium	Medium
Acid reaction	Furfural	0.75	1.45	1.09	286	Medium	Medium
Sugar	Sugar syrup	1.00	0.22	0.22	Large	None	Medium
<u>Candida utilis</u>	SCP	0.50	0.30	0.15	Large	Low	Medium

Sources: Underkoffler and Hickey (1954); Anon. (1981, 1983); Schwester et al. (1983).

^a To butadiene.

Various uses have been proposed for hemicellulose, e.g., an extrudent gum (Whistler and Zysk 1979), or super adsorbent (Anon. 1982b) but neither suggestion has been realized because the required purity is difficult to obtain. The most valuable product that can be obtained from the sugars of hemicellulose (xylose from hardwoods) is furfural (Table 8). The acid hydrolysis processes of American Can (Church and Wooldridge 1981) and Treeland Fuels and Chemicals (Anon. 1982a) are appropriately based on this route. If sugar is produced, the production of a sugar syrup or SCP would generate as much revenue as ethanol with lower processing costs.

Much research has been done on the possible utilization of lignin, the third major component of lignocellulosics, as a chemical source. The current practice in most pulp mills is to incinerate the solubilized lignin, yielding an energy credit of about \$0.08/kg (Table 9). Dimethylsulfoxide and vanillin are chemicals currently being produced from lignin, both are low-volume products so that some of the effluent is incinerated. The revenue generated by vanillin would be highly attractive but unfortunately the market demand for this product is not very large. Several processes to produce phenol and benzene from lignin have not yet had any commercial success (Goldstein 1975) but the most promising future high-volume usage of lignin will probably be in polymeric resins (Graff 1982). However, high-grade lignin produced by expensive solvent extraction or steam explosion may be a prerequisite.

Several other options do not require the separation of the lignocellulosic components because certain organisms have the enzymatic capability to hydrolyze the cellulose and hemicellulose fractions and metabolize them to end products. This is the basis of the Massachusetts Institute of Technology's (MIT) ethanol production system (Jenkins and Reddy 1979) and various SCP processes such as the one at the University of Waterloo (Moo-Young et al. 1978a). Anaerobic biological digestion is also a process that can utilize lignocellulosics directly and can produce either methane or, if the methanogenic group of bacteria is inhibited, volatile fatty acids. It would be potentially much more economical to produce fatty acids (as a storage intermediate) than methane directly (Table 10); the fatty acids route to SCP also has economic potential. Several schemes have been proposed for utilization of the fatty acids, for example, producing hydrocarbons by electrolytic reduction (Levy et al. 1982), producing fatty acid esters for gasoline additives (Datta 1981), and growing *Candida utilis* for animal feed (Thomas and Evison 1978). Another route is gasification of the biomass followed by the utilization of the synthesis gas by organisms to produce chemicals (Levy et al. 1981).

Table 9. Possible uses of lignin

Product	Yield (kg/kg lignin)	Product value (US\$/kg)	Maximum possible revenue (US\$/kg lignin)
Burn for heat	1.00	0.08	0.08
DMSO	0.03	1.72	0.13 ^a
Vanillin	0.07	11.56	0.89 ^a
Phenol	0.20	0.70	0.14
Benzene	0.14	0.58	0.08
Total	-	-	0.22
Resins	1.00	0.35	0.35

Source: Goldstein (1975); Graff (1982); Anon. (1983).

^a Credit for heating value included.

Table 10. Possible uses of fatty acids from anaerobic digestion

Products	Yield (per kg lignocellulose)	Yield (per kg glucose and xylose in wood)	Product value (US\$)	Maximum possible revenue (US\$/kg glucose and xylose in wood)
Fatty acid production	0.50 kg	0.70 kg	0.51/kg	0.36
SCP from fatty acids	0.825 kg	1.155 kg	0.30/kg	0.35
Methane from fatty acids	0.26 m ³	0.35 m ³	0.15/m ³	0.05

Source: Anon. (1983).

Future of Bioconversion of Lignocellulosic Biomass

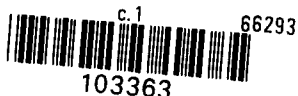
Even though methanol seems to be an attractive route to liquid fuels and certain chemicals from lignocellulosic materials, large-scale plants are required to test the economics. Large centralized sources of waste biomass would be required, a situation that is not found too often. Methanol can also be made from gasified coal or peat moss (concentrated nonrenewable resources) and this could be a more economical (but possibly more polluting) route. Ethanol produced for solvent purposes by fermentation can be competitive with the energy-intensive synthetic production route from ethylene now being used. However, it should be noted that ethanol via synthesis gas could also compete in this market.

Because biomass is a rather diffuse resource, emphasis should be placed on developing simple systems that can be practical and economical on a small scale. We have proposed a system that could be integrated into a rural setting, producing fuel (e.g., methane) and feed (e.g., SCP) for recycle back into the ecological system (Moo-Young et al. 1978b). If wood wastes are used, chemicals could be produced that are not easily synthesized via methanol. Elaborate, high technology methods of pretreatment should be avoided and more direct routes using anaerobic digestion, cellulolytic organisms, or possible gasification should be developed. Several technical breakthroughs are still required before the pretreatment/fermentation route to ethanol is economical. If this route is taken using present technology, higher-value products than ethanol should be produced. One suggestion is that high-priced potable beverage-grade ethanol should be produced instead of the cheaper fuel-grade variety. It could turn out to be indeed more profitable to fill people's stomachs instead of their gas tanks.

References

- Anonymous. 1981. Chemical marketing economics handbook. US Bureau of Census, Washington, DC, USA.
- Anonymous. 1982a. Biomass Digest, April, 4-5.
- Anonymous. 1982b. Biomass Digest, June, 4-5.
- Anonymous. 1983. Chemical Marketing Reporter, 223(13). Schnell Publishing Co., New York, NY, USA.

- Church, J.A., and Wooldridge, D. 1981. Continuous high-solids acid hydrolysis of biomass in a 1½ in. plug flow reactor. IEC Product Research and Development, 20, 371-378.
- Datta, R. 1981. Production of organic acid esters from biomass -- Novel processes and concepts. Biotechnology and Bioengineering Symposium, 11, 521-532.
- Goldstein, I.S. 1975. Perspectives on production of phenols and phenolic acids from lignin and bark. Applied Polymers Symposia, 28, 259-262.
- Graff, G.M. 1982. High-grade lignin schemes edge closer to reality. Chemical Engineering, 89, 25-27.
- Haggin, J., and Krieger, J.H. 1983. Biomass becoming more important in US energy mix. Chemical Engineering News, 61(11), 28-30.
- Jenkins, D.M., and Reddy, T.S. 1979. Economic evaluation of the MIT process for manufacture of ethanol. Battelle Columbus Laboratories, Columbus, OH, USA, Laboratory Report.
- Katzen, R., Messick, J.R., and Moon, G.D. 1979. Biomass processes -- Systems evaluation and economic analysis. In 3rd Annual Biomass Energy Systems Conference Proceedings, Golden, Colorado, 5-7 June.
- Keim, C.R. 1983. Technology and economics of fermentation alcohol -- An update. Enzyme Microbiology and Technology 5(3), 103-114.
- Kitchen, C.D., and Tong, G. 1982. Impact of new technology on ethanol production costs. In Proceedings of 2nd World Congress of Chemical Engineering, Montreal, 4-9 October 1981. Canadian Society of Chemical Engineers.
- Kovaly, K.A. 1982. Biomass process handbook. Technical Insights Inc., Fort Lee, NJ, USA.
- Lencki, R.W., Robinson, C.W., and Moo-Young, M. 1983. Improving the energy efficiency of separating ethanol from fermentation broths. In Symposium on Biotechnology for Fuels and Chemicals 1983. Biotechnology and Bioengineering Symposium, in press.
- Levy, P.F., Barnard, G.W., Garcia-Martinez, D.V., Sanderson, J.E., and Wise, D.L. 1981. Organic acid production from CO₂/H₂ and CO/H₂ by mixed-culture anaerobes. Biotechnology and Bioengineering Symposium, 23, 2293-2296.
- Levy, P.F., Sanderson, J.E., and Wise, D.L. 1982. Development of a process for production of liquid alkane fuel from biomass. In Proceedings 2nd World Congress of Chemical Engineering, Montreal, 4-9 October 1981. Canadian Society of Chemical Engineers.
- Mackay, D., and Sutherland, R. 1976. Methanol in Ontario -- A preliminary overview report. Report for the Ontario Ministry of Energy, Toronto, Ont., Canada.
- Moo-Young, M., Daugulis, A.J., Chahal, D.S., and Macdonald, D.G. 1978a. The Waterloo process for SCP production from waste biomass. Process Biochemistry, 14(10), 38-40.
- Moo-Young, M., Moreira, A., Daugulis, A.J., and Robinson, C.W. 1978b. Bioconversion of agricultural wastes into animal feed and fuel gas. Biotechnology and Bioengineering Symposium, 8, 205-218.
- Perez-Blanco, H., and Hannon, B. 1982. Net energy analysis of methanol and ethanol production. Energy, 7(3), 267-280.



- Phillips, C.R., Granatstein, D.G., and Wheatley, M.A. 1979. Potential of biomass to substitute for petroleum in Canada. ACS Symposium Series, 90, 133-164.
- Robinson, C.W., Moo-Young, M., and Lamprey, J. 1981. Ethanol production by immobilized yeast cells in a packed tower. In Moo-Young, M., and Robinson, C.W., eds. Advances in biotechnology, Vol. II. Pergamon Press, Elmsford, NY, USA.
- Schooley, F.A., et al. 1978. Mission analysis for the federal fuels from biomass program. In Symposium on Fuels from Biomass, RPI, Troy, NY, 20 June.
- Schvester, P., Robinson, C.W., and Moo-Young, M. 1983. Production of ethanol from xylose: Comparison of direct and indirect fermentations. In Symposium on Biotechnology for Fuels and Chemicals 1983. Biotechnology and Bioengineering Symposium, in press.
- Sherwin, M.B. 1981. Chemicals from methanol. Hydrocarbon Processing, 60(3), 79-84.
- Stone, J.E. 1982. Analysis of ethanol production potential from cellulosic feedstocks. Report for Conservation and Renewable Energy Branch, Energy, Mines and Resources Canada, Ottawa, Ont., Canada.
- Thomas, K., and Evison, L.M. 1978. A new approach to anaerobic digestion: Process control to produce effluents suitable for SCP recovery. In Mattock, G., ed. New processes of waste water treatment and recovery. Ellis Harward Ltd., Chichester, Sussex, UK.
- Underkoffer, L.A., and Hickey, R.J. 1954. Industrial fermentations. Chemical Publishing Co. Inc., New York, NY, USA.
- Whistler, R.L., and Zysk, J.R. 1979. Carbohydrates. In Encyclopedia of chemical technology, Vol. 4. John Wiley and Sons, New York, NY, USA.
- Worthy, W. 1981. Cellulose-to-ethanol projects losing momentum. Chemical Engineering News, 59(49), 35-42.