Solar energy through biology: fuels from biomass

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1. *Introduction*[1-6]

Hardly a day goes by without there being a news item warning us of the impending shortage of oil and what it is going to cost us - assuming we can get it! The belated realization that non-renewable liquid fuels are going to increase in price, and possibly even be rationed, is one of the main reasons why biomass is being looked into so seriously by so many of the developed countries. For the developing countries, the energy problem is as acute - if not more so. The 'woodfuel crisis' is revealing the long-term detrimental agricultural, social and economic consequences of deforestation.

The majority of the people in the world live by raising plants and by processing their products, but now, their governments - and most particularly the governments of developing nations - are confronted with the critical problem of maintaining and possibly increasing consumption without harming ecological systems. A more efficient use of existing biomass and energy alternatives upon which technology is solar- and wind-based is absolutely essential if the present trend of excessive biomass use is to be reversed. The biomass that provides a source of energy now can continue to do so in the future - but to what extent it will be able to contribute to the overall provision of energy will very much depend on the special economic and geographic circumstances within any given country, and the extent to which each country is capable of realistically assessing and planning for its energy requirements in the future.

The oil and energy problem of the last 8 years has already made a clear impact on the use and development of biomass energy. First, in the developing countries there has been an accelerated use of biomass as oil products have become too expensive or even unavailable. Second, in a number of developed countries large research and development programs have been instituted to establish the potential and costs of energy from biomass. Estimated current expenditure is over $100 million per annum in North America and Europe. While this work is still in its early stages, results look far more promising than was thought possible even three years ago. Finally, already in Brazil for example, (a country which currently spends over half of its foreign currency on oil imports), large scale biomass energy schemes are being implemented as rapidly as possible - the current investment is over one billion dollars per annum.

It is well-known that all our fossil carbon reserves are products of past photosynthesis. Photosynthesis is *the* key process in life and, as performed by plants, can be simply represented as

$$H_2O + CO_2 \xrightarrow[\text{solar energy}]{\text{plants}} \text{organic materials} + O_2$$

In addition to C, H and O, the plants also incorporate nitrogen and sulphur into the organic material via light-dependent reactions - this latter function is often not appreciated.

Where, in the past, photosynthesis has given us coal, oil and gas, fuelwood, food, fiber and chemicals, it now seems necessary to look at how photosynthesis fits into the biosphere and explore in what new ways solar energy conversion can become a source of raw materials in the future.

Most people are not aware of the magnitude of present photosynthesis: it produces an amount of stored energy in the form of biomass which is roughly 10 times the amount of energy which the world uses annually. Table 1 shows that the total amount of proven fossil fuel reserves below the earth is only equal to the present standing biomass (mostly trees) on the earth's surface while the fossil fuel resources are probably only 10 times this amount. This massive-scale capture of solar energy and conversion into a stored product occurs with only a low overall efficiency of about 0.1% on a world-wide basis, but because of the adaptability of plants it takes place and can be used over most of the earth.

It is not widely appreciated that 15% of the world's annual fuel supplies are biomass (equivalent to 20 million barrels of oil a day - the same as the USA consumption rate) and that about half of all the trees cut down are used for cooking and heating. This use is confined mostly to developing countries where biomass in rural areas supplies more than 85% of the energy. Total biomass energy in these countries is approximately 4×10^{10} GJ annually. In the non-OPEC developing countries, which contain over 40% of the world's population, non-commercial fuel (including wood, dung and agricultural wastes) accounts for up to 90% of the total energy used. Total woodfuel consumption is probably 3 times that usually shown in statistics; supply statistics of non-commercial energy can be out by factors of 10 or even 100.

In the present paper, I would like to expand on this evidence that fuels produced by solar energy conversion are a very important source of energy now and will continue to be increasingly so in the forseeable future. However, with today's increased population and standard of living, we cannot rely only on old technology, but must develop new means of utilizing present-day photosynthetic systems more efficiently. Solar biological systems could be realized to varying degrees over the short and long term and some systems using, for example, wood, biological and agricultural wastes, and energy farming, could be put into practice immediately. Photobiological systems can be tailored to suit an individual country according to the energy available, local food and fiber production, ecological aspects, climate and land use. In all cases the total energy input (other than sunlight) into any biological system must be weighed against the energy output and also against the energy consumed in the construction and operation of any other competing energy producing system.

Table 1. Fossil fuel reserves and resources, biomass production and CO_2 balances (Hall[1])

Proven reserves	Tonnes coal equivalent
Coal	5×10^{11}
Oil	2×10^{11}
Gas	1×10^{11}
	8×10^{11} t $= 25 \times 10^{21}$ J
Estimated resources	
Coal	85×10^{11}
Oil	5×10^{11}
Gas	3×10^{11}
Unconventional gas and oil	20×10^{11}
	113×10^{11} t $= 300 \times 10^{21}$ J
Fossil fuels used so far (1976)	2×10^{11} t carbon $= 6 \times 10^{21}$ J
World's annual energy use	3×10^{20} J (5×10^{9} t carbon from fossil fuels)
Annual photosynthesis	
a) Net primary production	8×10^{10} t carbon (2×10^{11} t organic matter) $= 3 \times 10^{21}$ J
b) Cultivated land only	0.4×10^{10} t carbon
Stored in biomass	
a) Total (90% in trees)	8×10^{11} t carbon $= 20 \times 10^{21}$J
b) Cultivated land only (standing mass)	0.06×10^{11} t carbon
Atmospheric CO_2	7×10^{11} t carbon
CO_2 in ocean surface layers	6×10^{11} t carbon
Soil organic matter	$10\text{-}30 \times 10^{11}$ t carbon
Ocean organic matter	17×10^{11} t carbon

These data, although imprecise, show that a) the world's annual use of energy is only $1/10$ the annual photosynthetic energy storage, b) stored biomass on the earth's surface at present is equivalent to the proven fossil fuel reserves, c) the total stored as fossil fuel carbon only represents about 100 years of net photosynthesis, and d) the amount of carbon stored in biomass is approximately the same as the atmospheric carbon (CO_2) and the carbon as CO_2 in the ocean surface layers.

Solar energy is a very attractive source of energy for the future but it does have disadvantages. It is diffuse and intermittent on a daily and seasonal basis, thus collection and storage costs can be high. However, as plants are designed to capture diffuse radiation and store it for future use, very serious thought (and money) is being given to ideas promoting biomass as a source of, for example, liquid fuels and also for power generation (table 7). I am aware of biomass programs in the UK, Ireland, France, Germany, Denmark, Sweden, USA, Canada, Mexico, Brazil, Sudan, Kenya, Zimbabwe, Australia, New Zealand, India, Indonesia, Philippines, Thailand, Israel, South Korea and China. The greatest obstacle in implementing them seems to lie in the simplicity of the idea - the solution is too simple for such a complex problem! Fortunately for us, plants are very adaptable and exist in great diversity - they could continue indefinitely to supply us with renewable quantities of food, fiber, fuel and chemicals. If the serious liquid fuel problem which is predicted to befall us within the next 10-15 years comes about, we may turn to plant products sooner than we axpect. Let us be prepared!

What I am definitely not suggesting is that any one country should or will ever be able to derive all its energy requirements from biomass; this is highly unlikely except under especially favorable circumstances. What each country (or even region), should do, however, is to look closely at the advantages of and problems with biomass energy systems (table 2). The long term advantages are considerable but implementation of significant programs will take time and require important economic and political commitments. The programs will vary in their emphasis and thus most of the research and development should be done locally. Such R & D is an ideal opportunity to encourage the work of local scientists, engineers and administrators in one field of energy supply. Even if biomass systems do not become significant suppliers of energy in a specific country in the future, the spin off in terms of benefits to agriculture, forestry, land use patterns and bioconversion technology can, I think, be significant.

2. *Efficiency of photosynthesis*[5]

Plants use radiation between 400 and 700 nm, the so-called photosynthetically active radiation (PAR). This PAR comprises about 50% of the total sunlight which (total) on the earth's surface has an average normal-to-sun daytime intensity of about 800-1000 W/m^2.

The overall practical maximum efficiency of photosynthetic energy conversion is approximately 5-6% (table 3) and is derived from the process of CO_2 fixation and the physiological and physical losses involved. Fixed CO_2 in the form of carbohydrate has an energy content of 0.47 MJ/mol of CO_2 and the

Table 2. Some advantages and problems foreseen in biomass for energy schemes (Hall[2])

Advantages	Problems
1 Stores energy	1 Land use competition
2 Renewable	2 Land areas required
3 Versatile conversion and products; some products with high energy content	3 Supply uncertainty in initial phase
	4 Costs often uncertain
4 Dependent on technology already available with minimum capital input; available to all income levels	5 Fertilizer, soil and water requirements
	6 Existing agricultural, forestry and social practices
5 Can be developed with present manpower and material resources	7 Bulky resource; transport and storage can be a problem
	8 Subject to climatic variability
6 Large biological and engineering development potential	
7 Creates employment and develops skills	
8 Reasonably priced in many instances	
9 Ecologically inoffensive and safe	
10 Does not increase atmospheric CO_2	

energy of a mole quantum of red light at 680 nm (the least energetic light able to perform photosynthesis efficiently) is 0.176 MJ. Thus the minimum number of mole quanta of red light required to fix 1 mole of CO_2 is $0.47/0.176 = 2.7$. However, since at least 8 quanta of light are required to transfer the 4 electrons from water to fix 1 CO_2, the theoretical CO_2 fixation efficiency of light is $2.7/8 = 33\%$. This is for red light, and obviously for white light it will be correspondingly less. Under the most optimal field conditions values of 3% conversion can be achieved by plants; however, often these values are for short-term growth periods, and when averaged over the whole year they fall to between 1 and 3%.

In practice, photosynthetic conversion efficiencies in temperate areas are typically between 0.5 and 1.3% of the total radiation when averaged over the whole year, while values for sub-tropical crops are between 0.5 and 2.5%. The yields which can be expected under various sunlight intensities at different photosynthetic efficiencies can be easily calculated from graphical data.

Table 3. Photosynthetic efficiency and energy losses[5]

	Available light energy
At sea level	100%
50% loss as a result of 400–700 nm light being the photosynthetically usable wavelengths	50%
20% loss due to reflection, inactive absorption and transmission by leaves	40%
77% loss representing quantum efficiency requirements for CO_2 fixation in 680 nm light (assuming 10 quanta/CO_2)*, and remembering that the energy content of 575 nm red light is the radiation peak of visible light	9.2%
40% loss due to respiration	5.5%
	(Overall photosynthetic efficiency)

* If the minimum quantum requirement is 8 quanta/CO_2, then this loss factor becomes 72% instead of 77%, giving the final photosynthetic efficiency of 6.7% instead of 5.5%.

3. *Implementation of biomass energy schemes*[2, 7–9]

The main factors which will determine whether a biomass scheme can be implemented in a given country are a) the biomass resource, b) the available technology and infrastructure for conversion, distribution and marketing, and c) the political will combined with social acceptance and economic viability. These points are now considered in turn.

a) *The resource base*

The total annual production of biomass (net primary production), the amount of wood produced (including natural forest and managed plantations), and the harvested weight of the major starch and sugar crops are shown in table 4. In addition, there is a worldwide availability of crop residues and other organic wastes (table 5). Although the amount of such wastes has been calculated in some detail for the USA, Canada and certain European countries, where they have been identified as the major short term biomass-resource, such figures are not generally available for the developing countries. Such data that are available are often questionable and cannot, at present, form a basis for any energy planning discussions. In addition to established sources of wood and food, a wide range of other land and aquatic cultivation systems have been proposed for the future. Both established and future options are summarized in table 5. Two usually neglected resources must be mentioned, viz. aquatic plants and algae and also arid land plants.

b) *Technology for conversion*

Biomass as it stands in the field or is collected as wastes is often an unsuitable fuel since it has a high moisture content, a low physical and energy density

Table 4. Annual biomass production in tonnes[7]

Net primary production (organic matter)	2×10^{11}
Forest production (dry matter)	9×10^{10}
Cereals (as harvested)	1.5×10^{9}
as starch	1×10^{9}
Root crops (as harvested)	5.7×10^{8}
as starch	2.2×10^{8}
Sugar crops (as harvested)	1×10^{9}
as sugar	9×10^{7}

and is incompatible with present demands that a fuel be used in internal combustion engines, the main power source for transport and agriculture in most countries. Established conversion technology can be divided into the biological and the thermal (table 6). The great versatility of biomass energy systems is one of their most attractive features - there is a range of conversion technologies already available (and being improved) yielding a diversity of products, especially liquid fuels to which the world seems addicted and upon which most world economies have recently been based.

Plant materials may be degraded biologically by anaerobic digestion processes or by fermentation, the useful products being methane, ethanol and possibly other alcohols, acids and esters. At present the established technologies are the anaerobic digestion of cellulosic wastes to form methane or the fermentation of simple sugars to form ethanol. The most suitable feedstocks for anaerobic digestion are manures, sewage, food wastes, water plants and algae.

The most suitable materials for thermal conversion are those with a low water content and high in lignocellulose, for example wood chips, straw, husks, shells of nuts, etc. The most likely processes to be adopted will use part of the material as fuel for the production of the required mixture of carbon monoxide and hydrogen (synthesis gas) for the subsequent catalytic formation of alcohols and hydrocarbons. During gasification oxygen or steam may be introduced in order to enhance the degree of conversion to synthesis gas and to increase its purity.

Two basic routes of catalytic conversion, of synthesis gas to further products can be recognized. The gas may be converted directly to hydrocarbons via the Fisher-Tropsch synthesis, or may be used for the formation of methanol. Both routes are well established in connection with use of gas produced from coal with plants operating in countries such as South Africa and Germany. Some plants using sorted domestic rubbish are operating and considerable research is being carried out on gasification of wood. On a smaller scale commercial wood-fueled gasification plants have been available for some time, the gas produced being suitable for use in stationary engines.

Table 5. Sources of biomass for conversion to fuels[7]

Wastes	*Land crops*	*Aquatic plants*
Manures	*Ligno-cellulose crops*	*Algae*
Slurry	Trees: Eucalyptus	Uni-cellular:
Domestic rubbish	Poplar	*Chlorella*
Food wastes	Firs, pines	*Scenedesmus*
Sewage	*Leuceana,*	*Navicula*
	Casuarina	Multi-cellular:
Residues	*Starch crops*	Kelp
Wood residues	Maize	
Cane tops	Cassava	*Water plants*
Straw		Water hyacinth
Husks	*Sugar crops*	Water reeds/rushes
Citrus peel	Cane	
Bagasse	Beet	
Molasses		

c) *Energy ratios and economics*

In an ideal world the main factors to be considered in adopting a specific biomass route would relate to the energy gain and the economics. The benefit to be derived by converting plant material to ethanol for example can be expressed in terms of the net energy ratio (NER) which is obtained by dividing the final yield of energy in useful products by the total energy inputs derived from sources other than the biomass itself. In computing the inputs, in addition to fuel, fertilizer and irrigation, a value has to be assigned to the farm and process machinery and to ongoing maintenance. In general a net energy gain is seen where the fermentation and distillation is powered by the burning of crop residues, as in the case of sugar cane, or by burning of wood obtained from close by - as for a cassava alcohol-distillery powered using Eucalyptus wood. Reported NER values for such systems vary from about 2.4 to over 7. For most starch

Table 6. Solar energy for fuels: conversion process and products[7]

Resource	Process	Products	Users
Dry biomass (e.g. wood, residues)	Combustion	Heat, electricity	Industry, domestic
	Gasification	Gaseous fuels → methanol, hydrogen, ammonia	Industry, transport, chemicals
	Pyrolysis	Oil, char, gas	Industry, transport
	Hydrolysis and distillation	Ethanol	Transport, chemicals
Wet biomass (e.g. sewage, aquatics)	Anaerobic digestion	Methane	Industry, domestic
Sugars (from juices & cellulose)	Fermentation and distillation	Ethanol	Transport, chemicals
Water	Photochemical/photobiological catalysis	Hydrogen	Industry, chemical, transport

Simplified table: numerous cross-links exist. Agriculture included in industry. Many important final products not listed.

crops and sugar beet the values are close to or below 1, i.e., more energy is used than is produced. However, this may still be worthwhile if the fuel source is for instance cheap coal of poor quality, wood or residues, etc., which are in effect converted to a high quality fuel.

For the thermal conversion routes an efficiency can be calculated as the ratio of energy in the end product as a fraction of the energy content of the starting material. Since part of the feed is completely combusted to power the conversion, this value must be less than 1. Here the justification is again related to the production of a high quality, higher energy density liquid fuel, from a bulky wet biomass source. At present the efficiency of methanol production from wood is probably about 25%, however efficiencies of around 60% are theoretically feasible.

The estimates of the cost of producing alcohol by fermentation of biomass vary enormously from US 10c/ l to over 60c/l. However, many of these estimates are based on paper studies. Realistic figures from Brazil (1979) are as follows: 30.5c/l for sugar cane alcohol and 31.7c for cassava-derived alcohol as compared to gasoline at an ex-refinery selling price of 23c/l and a retail price of 39.6c/l. The alcohol prices are FOB distillery selling prices calculated for alcohol produced by autonomous distilleries computed to yield the investor a 15% annual return on investment calculated according to the discounted cash flow method and on Proalcool funding of 80% of the fixed investment. Ethanol production, from farm crops, in the USA is profitable at present due to the tax structure. The Federal Government has passed an exemption of gasoline tax on Gasohol (a 10% ethanol:gasoline blend) equivalent to $0.4 per gallon. Various states offer further tax incentives: in Iowa, for instance, the combined subsidies work out at over $1 per gallon. The justification for this lies in the fact that in order to maintain corn prices the government subsidizes each bushel of corn *not* produced with 1 dollar. A bushel of corn can produce 2.5 gallons (US) of ethanol to be used in 25 gallons of gasohol.

Most paper studies indicate that methanol produced by gasification of wood and catalytic resynthesis will be considerably cheaper than ethanol produced by fermentation. The only problem is that no production plants are operating at present. A detailed analysis for a methanol plant in New Zealand can be summarized as follows. At an efficiency of 50% for a 2500 oven-dry tons per day plant at 1977 prices using NZ national cost benefit economics (10% on capital, DCF over 30 years, no tax or depreciation) the product price was $214 per ton using wood at $55 a ton or $146 a ton for wood at $25 a ton. These values are equivalent to product costs of between 17 and 19c a liter, comparable with those summarized recently by the US Solar Energy Research Institute (SERI) where methanol costs from wastes or fuel crops varied from 11c to 35c/l at raw material costs from a negative value for waste to about $50 a ton, with assumed efficiencies of methanol production of between 25 and 50%.

d) *Implementation*

I have already mentioned that the assessment and implementation of biomass energy programs in individual countries is an excellent opportunity for a country to develop its own research, and to demonstrate its capabilities in this area. The types of biomass available for conversion to energy are very much region-dependent, e.g., sugar cane and cassava in hotter climates, cellulose in temperate areas and hydrocarbon shrubs in arid zones. No one country has a monopoly on biomass-for-energy expertise. Indeed the expertise is widespread - note the ethanol program in Brazil, the biogas plants in China and India, gasifiers in Germany, straw burners in Denmark, agro-forestry in East Africa, village woodlots in Korea and parts of India, and so on. There is also the opportunity to encourage collaboration among scientists, engineers, foresters, agronomists, sociologists, economists, and administrators within regions within a country, and among countries. Biomass conversion to energy is an 'old-but-new' and rapidly developing area which interests many young scientists and engineers because it has both immediate practical and also longer-term basic research and development features.

It is imperative that in individual countries accurate energy assessments be made of energy flows, priority needs and available resources; at the same time, the limitations of the data at hand must be recognized. Proposals to implement biomass energy systems must be specific. But even then, policy changes can be effected only if the energy programs have the full support of the decision makers and the people themselves who are convinced of the practical importance of these systems. Otherwise, as experience shows, nothing can be accomplished.

4. *Status of existing biomass projects*

In tables 7 and 8 a short summary of biomass and energy costs of some schemes around the world are listed. Further details are given for a number of these schemes in the references cited[6,10,11]. At present, I will briefly refer only to some European studies.

In Europe a number of countries and the EEC are conducting extensive feasibility studies on the potential which biomass may have for supplying a source of energy and fuels in the future. Trial plantings of alder, willows, poplars, etc., are being undertaken in addition to assessing energy yields from agricultural residues, urban wastes, techniques of conversion, waste land and forest potentials, and algal systems. Biological and thermal conversion equipment is available

Table 7. Estimated biomass and energy product costs (various countries)[1]

Country	Product and source	Cost
1. Brazil (1977)	Ethanol from sugar cane	US$ 16.7/10^6 BTU
	(ex distillery)	US$ 0.33/l
	Gasohol (retail)	US$ 13.18/10^6 BTU
2. Australia (1975)	Ethanol from Cassava	AU$ 250/t
	Industrial ethanol	AU$ 275/t
3. Canada (1975 and 1978)	Methanol from wood	CAN$ 0.35–0.70/gallon
4. New Zealand (1976)	Ethanol from pine trees	NZ$ 260/t
	(500 t/day capacity; credits	(13% return on
	from byproducts)	capital)
5. New Zealand (1977)	Biogas from plants	NZ$ 3.45–5.57/GJ
	Natural gas production cost	NZ$ 1.09/GJ
	Coal gas production cost	NZ$ 6.33/GJ
6. Upper Volta (1976)	Fuelwood from plantation	US$ 0.09/kWh (t)
	Kerosene (retail)	US$ 0.13/kWh (t)
	Butane gas (retail)	US$ 0.11/kWh (t)
	Electricity	US$ 0.19/kWh (t)
7. Philippines (1977)	Electricity from *Leucaena* fuelwood-fired generating station	
	(same cost as oil-fired station)	US$0.014–0.018/kWh
8. Tanzania (1976)	Biogas from dung (for cooking and lighting)/Electricity	US$0.012/kWh
	Casvarina fuelwood to replace coalfired electricity generating station	US$0.113/kWh
9. India (Tamil Nadu) (1978)	(Competitive with coal: 15–30 year payback)	US$ 12/t (dry)

Table 8. Biomass energy product costs compared to conventional - USA (1981 estimate)[15]

Product	Cost from biomass ($/$10^6$ BTU)	Conventional cost ($/$10^6$ BTU)	Biomass: Conventional
Methanol	8.4–15.9	8.4	1.0–1.9
Ethanol	15.0–36.3	19.6	0.8–1.9
Medium BTU gas	4.7–7.4	3.0–5.0	0.9–2.5
Substitute natural gas	4.8–7.3	3.0–5.0	1.0–2.4
Ammonia	5.8–11.4	7.4	0.8–1.5
Fuel oil	3.6–7.9	3.2	1.1–2.5
Electricity	0.03–0.14 ($/kWh)	0.03–0.06 ($/kWh)	0.5–4.5

and is in great demand for use in Europe and for implementing overseas programs.

A recent study by the European Commission (Brussels) shows that in the 9 EEC countries biomass could provide 4% of their total energy requirements in the year 2000 (equal to 50 million tons of oil equivalent or 1 million barrels of oil per day) - this is the same as the agricultural sector's energy requirement and could be achieved with the use of residues and wastes and by utilizing some marginal land with minimal disturbance to conventional agriculture. With a great effort and disturbance to agriculture and forestry the EEC countries could provide 20% of their total energy requirements from biomass, if they so wished. In France, which estimates a biomass potential of 9 million tons oil equivalent by 1990, the large Government R & D program for solar energy gives priority to biomass for energy schemes. The EEC has a substantial biomass program and the UK also is supporting serious assessment and trial projects.

5. *Future photosynthesis*[12–14]

Whole plants

One of the 'problems' with photosynthesis is that it requires a whole plant to function - and the problem with whole plant photosynthesis is that its efficiency is usually low (less than 1%) since many limiting factors of the environment and the plant itself interact to determine the final overall efficiency. Thus a task for researchers of photosynthesis in the future will be to try to select and/or manipulate plants which will give higher yields with acceptable energy output/input ratios. We need much more effort placed on studies of whole plant physiology and biochemistry and their interactions with external (environmental) factors. Fortunately, however, this type of research is already being increasingly funded by both industrial and government organisations.

Examples of the areas in which research is being, or needs to be, done are: photosynthetic mechanisms of carbon fixation; bioproductivity; genetic engineering using plant cell tissue cultures; plant selection and breeding to overcome stresses (drought, temperature or salinity); selection of plants and algae yielding useful products such as oil, glycerol, waxes, or pigments; nitrogen fixation and metabolism and its regulation by photosynthesis.

Artificial photosynthesis

Also to be seriously considered is long-term basic, directed research on artificial photobiological/chemical systems for production of fuels and chemicals (H_2, fixed C, and NH_3); sustained funding will be needed if these exciting possibilities are to be realized.

Since whole plant photosynthesis operates under the burden of so many limiting internal and external factors, would it be possible to construct artificial systems which mimic certain parts of the photosynthetic processes and so produce useful products at higher efficiencies of solar energy conversion? (A 13% maximum efficiency of solar energy conversion is considered a practical limit to produce a storable product). I think that this is definitely feasible from a technical point of view but it will take some time to discover whether it could ever be economic. Note must also be taken of other chemical and physical systems (light driven) which are presently being investigated and may come to fruition before biologically-based systems do so.

A number of proposals have been made to mimic photosynthesis in vitro or to use in vivo photosynthesis in an abbreviated form in order to overcome the inefficiencies and instability factors that seem to be inherent in whole plant (or algal) photosynthesis. The state of the art is still very rudimentary, but we already have some idea of what may be achieved in the future - the scope is enormous, but it may well take 10 years or longer to discover whether any of these systems has any practical potential for the future. Fortunately, the quality of the work being done, and the wide interest and range of disciplines involved augurs profitable results.

Plants perform at least two unique reactions upon which all life depends, viz., the splitting of water by visible light to produce oxygen and protons and the fixation of CO_2 into organic compounds. An understanding of how these two systems operate and attempts to mimic the processes with in vitro and completely synthetic systems is now the subject of active research by biologists and chemists alike.

In vitro systems which emulate the plant's ability to reduce CO_2 to the level of organic compounds are being actively investigated. Recent reports claim the formation from CO_2 of methanol, formaldehyde and formic acid; this is the first time that light has been used outside the plant to catalytically fix CO_2. There has also been one report of the photochemical reduction of nitrogen to ammonia on TiO powder using UV-light.

One recently published idea deals with the photosynthetic reduction of nitrate to ammonia using membrane particles from blue-green algae. This process seems to occur naturally by light reactions closely linked (via reduced ferredoxin) to the primary reaction of photosynthesis, i.e., not involving the CO_2 fixation process. It is an interesting way to produce ammonia! However, it may be possible to use intact blue-green algae (immobilized?) to continually fix N_2 to NH_3 - the cells would have to be genetically derepressed and this is now certainly possible with the recent advances in genetics.

The term 'biophotolysis' is an abbreviation applied to photosynthetic systems that split water to produce hydrogen gas. This applies to both living systems, such as algae, and to in vitro systems comprising various biological components such as membranes and enzymes. We also discuss the so-called 'artificial' systems which seek to mimic the photosynthetic systems by the use of synthetic catalysts. Our bias tends to lean heavily on this last approach.

The great interest in biophotolysis-type systems probably derives from the fact that they are the only energy systems currently known to have the following three attributes: a) a ubiquitous, substrate (water) b) an unlimited driving force (the sun), and c) a stable and non-polluting product (hydrogen). At present, the biological system is the only one that is able to use wide range visible light to catalytically split water to H_2 and O_2; we hope that other systems will be found soon.

Photovoltages and photocurrents

Over the last few years, there have been a number of experiments aimed at constructing electrochemical devices based on the principle of charge separation in photobiological membrane systems. A common approach is to deposit the pigmented membranes onto electrodes (pure chlorophyll, mixtures of chlorophyll and organic redox compounds, chloroplast membranes, and reaction centers of photosynthetic bacteria have been used). Another approach has been to use the biological system with lipid membranes such as liposomes or BLMs (bacteriorhodopsin, photosynthetic reaction centres, and chloroplast membrane extracts have been used); stability has been improved by polymer incorporation into the BLM or by the use of lipid-impregnated Millipore filters. The characteristics of such systems have been described.

6. *Concluding statement*

Photosynthesis is the key process in the living world and will continue to be so for the continuation of life as we know it. The development of photobiological energy conversion systems has long term implications. We might well have an alternative way of providing ourselves with food, fuel, fiber and chemicals in the next century.

Suggested timetable for biomass-for-fuel programs

Next 10 years: Fuels from residues, trees and existing crops; use of existing biofuels; demonstrations and training.

10–20 years: Increased residue and complete crop utilisation, local energy crops and plantations in use.

After 20 years: Energy farming; improved plant species; artificial photobiology and photochemistry.

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Addendum. Since the completion of this article 4 symposia have been published which are of direct relevance to this article.

a W. Palz, P. Chartier and D.O. Hall, eds, Energy from Biomass. Applied Science Publishers, London 1981. 982 pp.
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Higher plants as energy converters

The first paper by S.H. Wittwer describes agriculture as the only major industry that processes solar energy. On one side this happens through photosynthesis and production of biomass. He discusses the possibilities for increasing the biomass yield for food, fiber and fuel as well as the use of sunlight for biological nitrogen fixation. On the other side solar energy can be used for many processes on the farm such as drying grain, heating livestock stables and greenhouses.

E.S. Lipinski and S. Kresovich discuss sugar crops (sugar cane, sugar beet and sweet sorghum) as important energy plants. They outline the features of each in cultivation and detail the procedures for processing and converting the crops into useful products and fuel.

M. Calvin et al. present plants with a high content of hydrocarbons, e.g. *Euphorbia* species, for energy crops on arid land. While these plants have a low requirement for water and nutrients, their production of biomass is relatively high.

F.H. Schwarzenbach and T. Hegetschweiler discuss energy conservation in trees and wood, the oldest form of biomass to be used as fuel by man. They deal primarily with the production of wood in the industrial countries of temperate climates rather than with energy farming in the tropical and subtropical zones.

Finally in the paper by N.W. Pirie, a special biomass product, leaf protein, is proposed as an alternative source of protein for food and fodder.

Solar energy and agriculture*

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Agriculture stands pre-eminent as the world's first and largest industry. It is our most basic enterprise, and its products are renewable as a result of 'farming the sun'. Through the production of green plants, agriculture is the only major industry that 'processes' solar energy. The greatest unexploited resource that strikes the earth is sunlight and the green plants are biological sun traps. Each day they store on earth 17 times as much energy as is presently consumed worldwide. The goal of agriculture is to adjust species and cultivars to locations, planting designs, cropping systems and cultural practices to maximize the biological harvest of sunlight by green plants to produce useful products for mankind. Many products of agriculture may be alternatively used as food, feed, fiber or energy. Conflicts over the agricultural use of land and water resources for food, feed or fuel production will arise as resource constraints tighten.