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Energy from the Biological Conversion of Solar Energy [and Discussion]

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Energy from the biological conversion of solar energy

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Trees and other forms of vegetation are well designed for the collection and storage of solar energy. Moreover, photosynthetic organisms show enormous diversity and are well adapted for a wide range of environments. Biomass is convertible to liquid and gaseous fuels by a number of established processes, and this paper examines the possible contribution of biomass to world energy demands.

The maximum efficiency of solar energy conversion in plant production is 5–6 %, but plants grown under usual field conditions do not achieve this degree of conversion. The highest yielding crops convert solar energy into plant material with an efficiency of 1–2 %, but the average yields of the major crops and forests indicate considerably lower efficiencies. The average efficiency of solar energy conversion on a global scale is estimated as about 0.15 %.

The energy content of the annual biomass residues in Australia and U.S.A. is equal to about one-quarter of the primary energy use in those countries, but only about one-third of the residues are considered to be readily recoverable.

A number of high yielding crops are examined as potential fuel crops. Energy inputs for growing non-irrigated crops in Australia are estimated to amount to 7–17 % of the solar energy stored in the total crop biomass. Irrigation adds considerably to the energy cost of producing crops. The overall energy efficiency of fuel production from biomass varies from 20 to 58 %, depending on the nature of the biomass and the process used to produce liquid or gaseous fuel. A recent estimate by an Australian committee of the potential contribution of biomass to liquid fuel production in Australia is presented.

It is concluded that biomass will not be able to provide a substantial fraction of the world's energy demand, although it can make a useful contribution.

INTRODUCTION

The two main disadvantages of solar radiation are its low energy density, which averages at the Earth's surface 150–200 W m^{-2} over 24 h, and its intermittent nature. Large surface areas of solar collectors are required to trap significant amounts of energy, and the collection arrays must be coupled to an energy storage system, if the Sun is to be used as a continuous energy source.

Trees and other forms of vegetation with large surface areas of leaves are well designed for the collection and storage of solar energy. Photosynthetic organisms show enormous diversity and are well adapted to a wide range of environments, both terrestrial and aquatic.

Man's dependence on the photosynthetic products of the past for his energy needs today is well illustrated by the distribution of primary energy use in the U.S.A. In 1975, the U.S.A. used 74.9×10^{18} J of primary energy or one-quarter of the World use of energy (Burwell 1978). Except for a small contribution (7 %) from hydroelectric and nuclear, the energy came from fossil fuels; 47 % from oil, 28 % from natural gas and 18 % from coal. In Australia, 98 % of the primary energy use (2.6×10^{18} J) is derived from fossil fuels with 47 % from oil, 8 % from natural gas and 39 % from coal (National Development 1978). Table 1, which shows the sector use of oil in Australia (National Development 1974), indicates that 52% is consumed in transportation. Fuel for transportation is the energy area of most concern in Australia, since the country's reserves of liquid petroleum will be severely depleted within a decade unless additional oil fields are discovered. It is predicted that there will be a world shortage of liquid petroleum by the turn of the century, failing the discovery of new oil fields.

Plant materials may be burnt directly for heating or converted by a number of established processes into liquid or gaseous fuels. This paper examines the possible contribution of biomass to World energy demands, particularly energy for transportation.

Table 1. Sector use of oil in Australia

sector	primary energy use in 1975–6 (10^{18} J)	 (percentage)
transport	0.65	52
industrial	0.37	29
domestic and commercial	0.10	8
power generation	0.06	5
agricultural and mining	0.08	6
total	1.26	100

PHOTOSYNTHESIS

Photosynthesis in green plants and algae is represented by the equation

$$H_2O + CO_2 \rightarrow (CH_2O) + O_2;\ \Delta G_0 = 0.47\ \text{MJ}.$$

The essential ingredients of photosynthesis are water, carbon dioxide and light. The products are oxygen and plant materials, represented in the equation by carbohydrate (CH_2O), although in the context of renewable resources it should be added that nitrogen, phosphorus and sulphur are also incorporated into plant products, and minerals are essential for plant growth. The free energy of the reaction, which is provided by solar energy absorbed by the plant pigments, is 0.47 MJ or 112 kcal.

The process of photosynthesis is divisible into two main phases, a light phase and a dark phase. In the light phase, quanta of radiation are absorbed by the chlorophylls and other photosynthetic pigments and converted into chemical energy in the form of reduced nicotinamide adenine dinucleotide phosphate (NADPH) and adenosine triphosphate (ATP). The formation of NADPH and ATP in photosynthesis involves two light reactions operating in sequence (Govindjee & Govindjee 1975). The O_2 which is evolved is derived from water. Photosynthesis thus involves the photolysis of water, but instead of the evolution of hydrogen gas, the reducing equivalents are used in the reduction of $NADP^+$. A minimum of 8 quanta of light are needed to produce the NADPH and ATP needed for the conversion of one molecule of CO_2 to carbohydrate (Govindjee & Govindjee 1975). The utilization of the NADPH and ATP for carbohydrate formation occurs in the dark phase of photosynthesis.

Efficiency of photosynthesis

The maximum efficiency of energy conversion in photosynthesis depends on the wavelength of the radiation (see table 2). For example, with red light of wavelength 680 nm the maximum efficiency is 33.3% and with blue light of wavelength 450 nm it is 22.1%. It must be stressed, however, that these are maximum efficiencies. They have been achieved under special conditions in the laboratory with isolated chloroplasts from higher plants or with algal cells.

Plants in the field growing under natural or cultivated conditions do not achieve, by a long way, these degrees of energy conversions for solar radiation. The factors which reduce the efficiency of solar energy utilization for plant production are shown in figure 1. Only about 45 % of solar radiation is at wavelengths that are absorbed by the photosynthetic pigments, the chlorophylls and the carotenoids. Of the solar energy incident on the leaves of a plant, about 35 % is absorbed by the chloroplasts, which are the subcellular bodies within the plant cells where the pigments are located and where CO_2 is transformed into carbohydrate. About 9–10 % of solar radiation is fixed in photosynthetic products, but nearly 50 % of this is lost by dark respiration and photorespiration. The net maximum efficiency is 5–6 %.

solar radiation incident on leaves
100 %
|
photosynthetically active wavelengths
45 %
|
absorbed by chloroplasts
35 %
|
fixed by photosynthesis
9–10 %
|
net efficiency after correction for dark
respiration and photorespiration
5–6 %

FIGURE 1. Maximum efficiency of solar energy utilization in plant production.

TABLE 2. MAXIMUM EFFICIENCY OF ENERGY CONVERSION IN PHOTOSYNTHESIS

wavelength of light/nm	energy per mol of quanta/MJ	percentage maximum efficiency†
350	0.342	17.2
450	0.266	22.1
550	0.218	27.0
650	0.184	32.0
680	0.176	33.3

† Calculated assuming 8 mol of quanta per mol CO_2 fixed and $\Delta G_0 = 0.47$ MJ.

Some peak growth rates and efficiencies of solar energy conversion of a number of crops grown in the field under optimal conditions are shown in table 3 (Denmead 1969; Stewart 1970; Loomis & Gerakis 1975). The efficiencies range from 2.7 % for *Pinus radiata* to 4.6 % for maize. The plants are shown in two groups: C_4-species, which possess the C_4-dicarboxylic acid pathway superimposed on the Calvin cycle for the assimilation of CO_2 (Hatch & Slack 1970), and C_3-species, which have the classical Calvin cycle. There is not a significant difference between the two groups, although it should be mentioned that C_4-species generally produce more dry matter for an equivalent use of water (Downes 1969). In the experiments in table 2, the plants were grown under very favourable conditions of temperature, water and nutrient supplies. It must be emphasized that the yields represent peak growth rates over relatively short growing periods.

Maximum growth rates averaged over the usual period of growth of a crop are considerably lower (see table 4) (Loomis & Gerakis 1975; Stewart 1970). For example, maize shows a growth rate, averaged over 117 days, of 23 g m^{-2} day^{-1}, compared with 52 g m^{-2} day^{-1} for the experimental crop of table 3. Sugarcane has a mean growth rate of 18 g m^{-2} day^{-1} over a whole year, or about one-half that of the experimental crop. The annual productivity of Napier grass (85 t ha^{-1}) represents an efficiency of solar energy conversion of 1.6%. Soybean, with a production of 8.9 t ha^{-1}, converts solar energy at an efficiency of 0.16%, if averaged over the whole year. Sugarcane shows an efficiency of 1.0% and cassava, 0.8%.

TABLE 3. MAXIMUM GROWTH RATES OF EXPERIMENTAL CROPS

crop	growth rate g m^{-2} day^{-1}	efficiency (percentage utilization of solar radiation)
C_4-species		
bulrush millet	54	4.2
maize	52	4.6
sugarcane	37	3.7
C_3-species		
rice	36	3.2
sugar-beet	31	4.5
soybean	27	4.4
pine (*Pinus radiata*)	41	2.7

TABLE 4. PRODUCTIVITY OF CROPS OVER USUAL GROWTH PERIODS

crop	location	length of growth period days	mean growth rate g m^{-2} day^{-1}	production t ha^{-1}
C_4-species				
maize	Colorado, U.S.A.	117	23	26.6
sugarcane	Hawaii, U.S.A.	365	18	67.3
Napier grass	El Salvador	365	23	85.3
Bermuda grass	Puerto Rico	365	10	37.3
bulrush millet	Katherine, Australia	112	19	21.3
forage sorghum	Australia	83	17	14.1
forage sorghum	California, U.S.A.	120	23	27.6
C_3-species				
sugar-beet	California, U.S.A.	240	14	33.8
sugar-beet	The Netherlands	160	14	22
alfalfa	California, U.S.A.	365	8	29.7
soybean	Japan	130	7	8.9
oil palm	Malaysia	365	8	29.4
cassava	Java	365	11	41

However, the average yields of the major crops and forests of the world are well below the figures of table 4. For example, the mean yield of the total biomass of the maize crop in the U.S.A. is 10.8 t ha^{-1}, representing an efficiency of solar energy conversion of 0.2% (Burwell 1978). Wheat in the U.S.A. shows an average biomass yield of 6.1 t ha^{-1} (Burwell 1978) and sugar beet in New Zealand a yield of 9.6 t ha^{-1} (Dent & Brown 1978).

Annual forest productivities of 8–15 t ha^{-1} have been reported for forests in Japan, Europe and North America (Kira 1975), evergreen forests being slightly more productive than deciduous forests. However, some recent statistics for forest production in the U.S.A. (Burwell 1978) indicate an average annual productivity of only 2.5–3.5 t ha^{-1}, representing 0.06 % efficiency of solar energy conversion. Eucalyptus forests growing naturally in Australia have even lower average annual yields (1.1–1.4 t ha^{-1}) (Ovington 1968). There is little doubt, however, that native forest productivity in U.S.A. and Australia could be increased many-fold by short rotation forestry and appropriate fertilizer application.

Table 5 indicates biomass yields from short-rotation hardwoods in U.S.A. (Benemann 1978) and Australia (Carter 1974). Annual yields of 10–20 t ha^{-1} were obtained, corresponding to an efficiency of solar energy conversion of 0.2–0.4 %.

Table 5. Biomass yields from short-rotation hardwoods

		yield t ha^{-1}	
sycamore	U.S.A.	11–16	coppiced
black cottonwood	U.S.A.	13	coppiced
poplar	U.S.A.	18	
eucalyptus	Australia	10–20	coppiced

Some estimates of world photosynthetic productivity have been published (Ryther 1969; Fogg 1968, 1975; Platt & Subba Rao 1975; Boardman 1977). Terrestrial plants are estimated to produce 10–14 × 10^{10} t dry matter per annum, and marine plants 7–8 × 10^{10} t. The total annual biomass production is equivalent to stored solar energy of 2.7–3.5 × 10^{21} J, which is about ten times more than the present world consumption of primary energy, but only three times more than the predicted consumption of energy in the year 2000.

The solar energy incident on the Earth's surface is 2 × 10^{24} J per annum, so that the total biomass production is equivalent to stored solar energy of 0.13–0.17 %. Since the oceans comprise 70 % of the Earth's surface, marine biomass productivity per unit area is only about one-quarter that of terrestrial biomass productivity.

For the U.S.A., total annual biomass production is estimated as 3.2 × 10^{9} t dry matter, which is equivalent to 56 × 10^{18} J of stored solar energy or three-quarters of the primary energy use in the U.S.A. (Pimental *et al.* 1978).

Potential availability of biomass for fuel production

This section of the paper summarizes recent estimates of biomass availability in Australia and the U.S.A. In May 1977, the C.S.I.R.O. organized a meeting to consider the potential contribution of biomass to Australia's energy requirements. As an outcome of that meeting, a small *ad hoc* committee was established under Mr G. A. Stewart to survey the potential production of liquid fuels from biomass in Australia by the turn of the century. The committee examined both existing biomass residues and new energy crops as feedstocks for liquid fuel production. The results of the survey will be published in the Bulletin series of the C.S.I.R.O. (Stewart *et al.* 1979). A summary of some of their conclusions is presented here, but the reader is referred to the forthcoming publication for the detailed analyses and the assumptions used.

Biomass residues

Estimates of annual biomass residues in Australia are shown in table 6 (Stewart *et al.* 1979). The forest residues are estimated as 9.3 Mt annually, but the proportion of this residue that could be realistically recovered for fuel production would depend on a number of factors, including accessibility of particular sites, cost of labour and size of conversion plants. Economy of scale in the production of liquid fuel would be expected from large conversion plants, but average transport costs from forestry sites to the conversion plant would be higher for larger plants. The recoverable residues from logging of *Eucalyptus* is usually about twice the quantity of usable logs. For pines, however, the recoverable logging residue is only about one-quarter the quantity of utilized saw logs (Stewart *et al.* 1979). Sawmills residues are estimated as 2–3 Mt annually.

TABLE 6. ANNUAL BIOMASS RESIDUES IN AUSTRALIA

	mass, dry Mt	energy content 10^8 J
forest	9.3	0.14
sawmill	2	0.07
cereal crops	28	0.42
sugarcane (bagasse)	3.2	0.05
urban solid wastes	4.5	0.07
total†	47	0.75

† Primary energy use in Australia = 2.7×10^{18} J.

Estimates for residues from cereal crops are based on current grain yields and data on the harvest index (i.e. ratio of grain yield to total above ground dry matter). Twenty-eight million tonnes of crop residues are available, wheat being the major crop, but it seems undesirable to remove all the cereal stubble. On sandy soils, cereal stubble left on the ground inhibits wind erosion, while on clayey soils it reduces water erosion. Soil structure and fertility also will be affected if all crop residues are removed annually. The Stewart committee suggested the return of about one-third of the residues to the soil, thus leaving about two-thirds available for collection and fuel production (Stewart *et al.* 1979).

Sugarcane is a major crop in Australia. Bagasse is the fibrous residue that remains after the juice is extracted from sugarcane. However, much of the bagasse is burnt as a fuel in the sugar mills. In addition to bagasse, the residues from growing sugarcane consists of the dry trash, which is burnt before harvest, and the remaining leaves and the top of the stem. The latter are removed by the harvester and discarded onto the ground. It is estimated that trash and tops could amount to 2.6 Mt (dry matter) (Stewart *et al.* 1979), but this quantity would only be available if new harvesting methods were introduced. It is not included in table 6. Urban solid wastes amount to 4.5 Mt. The total dry mass of biomass residues is 47 Mt, with an energy content of 0.75×10^{18} J, or about one-quarter of the primary energy use in Australia.

Annual biomass residues in the U.S.A. are shown in table 7 (Pimental *et al.* 1978). The total residues have an energy content of 18.2×10^{18} J, or about one-quarter of the primary energy use in U.S.A. which is very similar to the Australian situation. However, Benemann (1978) estimated that there were only about 328 Mt of readily recoverable wastes for fuel production in the U.S.A., i.e. about 30% of the total residues. Pimental *et al.* (1978) arrived at a similar conclusion; their estimate of recoverable residues was 372 Mt. Recoverable residues of this magnitude are equivalent to 5.6×10^{18} J, or 7% of the primary energy use in the U.S.A.

Table 7. Annual biomass residues in the U.S.A.

	mass, dry Mt	energy content 10^{18} J
forest	340	5.4
sawmill	81	1.3
crops	430	6.9
livestock manure (readily available)	128	2.0
urban wastes	123	2.0
industrial wastes	40	0.6
total†	1142	18.2

† Primary energy use in the U.S.A. = 75×10^{18} J.

Fuel crops

This section considers the potential for new crops, grown especially for the production of fuels. An important consideration in the selection of fuel crops is the energy budget, where the energy content of the crop is compared with the primary energy consumed (other than solar energy) in growing, harvesting and transporting the crop to the processing plant.

Table 8. Energy inputs and cost of possible energy crops

material	location	yield assumed t ha^{-1} a^{-1}	growing and harvesting cost \$ t^{-1}	transport cost \$ t^{-1}	energy input MJ t^{-1}
cassava					
tops	far north Queensland	12	24.50	3.50	870
tubers	far north Queensland	17.5	31.00	3.40	1210
eucalyptus	southeast Australia	16	17.40	1.50	760
kenaf	Ord River, W.A.	30	34.40	1.50	~ 2800
elephant grass	Burdekin Delta, Queensland	68	15.60	2.25	~ 840
sugarcane	Burdekin Delta, Queensland	44	16–21	2	—

McCann & Saddler (1976) proposed that high yielding crops offer the best prospects as fuel crops because of the lower relative costs of land preparation and harvesting. However, high yielding crops show a poorer energy budget (Burwell 1978). McCann & Saddler (1976) examined the energy budgets of five crops, selected for their ability to give high yields under commercial production: sugarcane, cassava (*Manihot esculenta* Crantz), kenaf (*Hibiscus cannabinus* L.), elephant grass (*Pennisetum purpureum*) and *Eucalyptus* spp. Cassava, which is commonly known as tapioca, is widely grown as a food in the tropics. It is an attractive fuel crop because it can give high yields of starch and total dry matter and is less affected than most other crops by droughts. Rapidly growing species of *Eucalyptus* have been grown in many countries. A feature of some species is their rapid regeneration after cutting (coppice formation), referred to earlier in this paper. Trees have an advantage over many crops; they can be harvested throughout the year, which means that processing plants would not remain idle for part of the year owing to lack of the feedstock. Kenaf is a rapidly growing annual and elephant grass (also known as Napier grass) is a perennial C_4-species with high annual yields.

Some estimates of energy inputs in growing, harvesting and transporting the crops to adjacent processing plants (average distance from crop to processing plant of 15 km) are summarized in table 8 (McCann & Saddler 1976; Saddler *et al.* 1976). Indicative costs at 1974 prices in

Australian dollars are also included ($A = $U.S. 1.13). The energy inputs represent only 5–6% of the energy content of the crop for elephant grass, cassava and *Eucalyptus* growing under rain-fed conditions and 18% for kenaf growing under irrigation in the Ord River scheme in Western Australia. Gifford (1975) estimated that the energy input in sugarcane growing in Australia represented 7–17% of the energy content of the crop. The total energy input in cropping in Australia is estimated as about 15% of the energy content of the total biomass (Gifford & Millington 1975; Gifford 1975).

TABLE 9. EFFICIENCIES OF FUEL PRODUCTION

product	raw material	cost/($ t^{-1})	comparable cost/($ GJ^{-1})	overall efficiency
ethanol	cassava	250	8.4	32
ethanol	eucalyptus	400	13.4	20
methane	cereal straw	235	4.2	44
pyrolytic oil	cereal straw	75	3.3	58
methane	eucalyptus	310	5.5	44
pyrolytic oil	eucalyptus	100	4.3	58

TABLE 10. COST OF FUELS

product	raw material	cost/($ t^{-1})	comparable cost/($ GJ^{-1})
ethanol	wheat grain ($85 t^{-1})	414–454	14.1–15.4
ethanol	eucalyptus ($45 t^{-1})	711	24.2
ethanol	sugarcane ($15 t^{-1})	359	12.3
methanol	wheat stubble ($12.3 t^{-1})	198	8.8

FUEL PRODUCTION

Established processes for converting organic materials to liquid and gaseous fuels are fermentation to ethanol, anaerobic fermentation to methane, pyrolysis to oil and formation of methanol via carbon monoxide and hydrogen. Sugars are easily fermented to alcohol, but starch and cellulose must first be hydrolysed either enzymically or with acid. Overall efficiencies for converting biomass to liquid or gaseous fuels are shown in table 9. These range from 20% for the production of ethanol from *Eucalyptus*, a ligno-cellulose source, to 58% for pyrolytic oil from *Eucalyptus* (McCann *et al.* 1976). Alcohol production from cassava has an efficiency of 32% and methane production from cereal straw 44%. The estimated costs of the fuels are also shown. Although the production of pyrolytic oil shows the best overall efficiency and cost, alcohol has a considerable advantage over crude oil as it can be used as a fuel in conventional internal combustion engines.

Some more recent estimates for costs of production of ethanol from crops and forests are given in table 10 (Stewart *et al.* 1979). Methanol production from wheat stubble is shown for comparison. Realistic prices for the organic feedstocks were used in these calculations; $A85 t^{-1} for wheat grain, $A15 t^{-1} for sugarcane, $A45 t^{-1} for *Eucalyptus* and $A12.3 t^{-1} for wheat stubble. Tables 9 and 10 indicate that liquid and gaseous fuels produced from biomass will be considerably more expensive than current fossil fuels. The comparative costs of some fossil fuels are: Kuwait oil at $U.S.10 per barrel, $A1.25 GJ^{-1}; no. 6 fuel oil, $1.7 GJ^{-1} and natural gas from the Cooper Basin in Australia $1.15 GJ^{-1} (McCann *et al.* 1976).

Potential contribution of biomass to liquid fuel production

Table 11, which summarized the recent studies of Stewart *et al.* (1979), shows the potential fuel production from various agricultural and forestry sources in Australia by the turn of the century. The amounts of fuel potentially available from the three main existing residues, i.e. residues from cereal grains, sugarcane and forests, equals 233×10^{15} J or about 33 % of current transport fuel use. Realistic assessments were made of the readily recoverable residues, and the efficiencies of conversion of the biomass to fuels. The reader is referred to the paper by Stewart *et al.* (1979) for full details.

Fuel crops on new lands provide liquid fuel equivalent to 412×10^{15} J, which is much greater than the amount estimated to be available from existing residues. The total production of liquid fuel from residues and new crops equals 645×10^{15} J, but some liquid fuel is used in producing the synthetic fuels from the biomass. The net liquid fuel production is 417×10^{15} J or about 60 % of current requirement for liquid fuel for transport in Australia. It is interesting to note that no single source contributes more than 17 % of current transport fuel needs. Stewart *et al.* (1979) suggests that other potential crop lands remain for development in the next century in northern Australia, particularly if new technologies for soil management are developed.

Table 11. Potential fuel from biomass in Australia

biomass	methanol	ethanol	total
	energy/(10^{-15} J)		
cereal grains			
existing residues	158	—	158
new fuel crops	78	121	199
sugarcane			
existing residues	34	2	36
new fuel crops	43	53	96
cassava			
new fuel crops	—	21	21
forests			
existing residues	39	—	39
new fuel crops	96	—	96
total liquid fuel product	448	197	645
net liquid fuel gain	287	130	417†

† Current transport liquid fuel use = 700×10^{15} J.

In the U.S.A., the biggest gains in biomass are likely to come from increasing the productivity of forests (Burwell 1978). However, a shift in food preference away from animal protein could release high quality agricultural land for energy crops. An analysis of potential energy farming in New Zealand showed that there is adequate land to supply New Zealand's liquid fuel requirements by the turn of the century (Harris 1978; Dent & Brown 1978). Brazil is producing large quantities of alcohol from sugarcane and has a plan to satisfy its liquid fuel requirements with alcohol from sugarcane and cassava. However, Brazil with its tropical climate, long growing season and large land area is well-endowed for the production of fuel crops. In Australia, five times the present area of sugarcane (currently 3.3×10^5 ha) could satisfy the nation's liquid fuel requirements for transport (Deicke *et al.* 1978) and 20 times would meet the total energy requirement, but suitable land of this magnitude for growing sugarcane is not available (Deicke *et al.* 1978).

CONCLUDING REMARKS

The average annual productivities of biomass presented in this paper, together with the energy budgets, suggest that biomass will not be able to contribute a substantial fraction of the World's energy demands. It is apparent that large areas of good productive land would be needed if land plants were to provide a large fraction of the World's energy. Even a high yielding crop, such as sugarcane, only has a productivity equivalent to a solar energy conversion efficiency of about 1%. The overall efficiency in converting biomass to liquid and gaseous fuel is 20–50%. If we accept an overall efficiency of 0.4% for the conversion of solar energy into a synthetic fuel (and this is probably over-optimistic), an area of good productive land equivalent to 10% of the land surface of the Earth would be required to meet the primary energy use of the world. Productive land areas of this magnitude are not available. Increasing demand for food will limit the land available for growing fuel crops.

However, photosynthesis can make a useful contribution, particularly in countries with a relatively low *per capita* consumption of energy or with large areas of rain-fed productive land. Calvin and his collaborators in California (Calvin 1977, 1978) are examining the growth of the *Euphorbias*, which store a useful fraction of their solar energy as hydrocarbons (10% of the dry weight of *Euphorbia lathyris* is hydrocarbon). Under irrigation the yield of the *Euphorbias* were equivalent to an annual production of about 25 barrels of oil per hectare (Calvin 1977, 1978). Calvin has suggested that 'petroleum plants' could be grown in semi-arid areas, which which are not suitable for conventional crops, but the yields of biomass under such non-irrigated conditions have not been determined. Hydrocarbon plants have the potential of meeting the feedstock requirements of the chemical industry.

In analysing the possible use of dry land areas for fuel crops, we must take into consideration the fragility of many of the semi-arid regions of the world. Environmental considerations also apply to any proposal that large areas of the Earth's surface could be used for short-rotation forestry.

Even if sufficient land areas were available for fuel crops, or if greater use could be made of the oceans for biomass production, solar energy via photosynthesis could not be regarded as a renewable energy resource, unless there was a complete recycling of non-renewable fertilizers, particularly phosphate. Because of the relatively poor photosynthetic efficiency of plants in the field and the requirement for fertilizers for plant growth, considerable research effort should be devoted to a more direct method of converting solar energy to a fuel.

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REFERENCES (Boardman)

Benemann, J. R. 1978 *Biofuels: a survey*. Electric Power Research Institute special report ER-746-SR Palo Alto, California.
Boardman, N. K. 1977 In *Living systems as energy converters* (ed. R. Buvet, M. J. Allen & J.-P. Massué), pp. 307–318. Amsterdam: North-Holland Publishing Co.
Burwell, C. C. 1978 *Science, N.Y.*, **199**, 1041–1048.
Calvin, M. 1977 *Energy Res.* **1**, 299–327.
Calvin, M. 1978 *Chem. Engng News* **56**, 30–36.
Carter, W. G. 1974 *Aust. Forestry* **36**, 214–225.
Deicke, R., Muller, R. L. & Bieske, G. C. 1978 In *Alcohol fuels*. Institution of Chemical Engineers, Sydney, Australia.

Denmead, O. T. 1969 *Agric. Met.* **6**, 357–371.
Dent, J. B. & Brown, W. A. N. 1978 In *Alcohol Fuels*. Institution of Chemical Engineers, Sydney, Australia.
Downes, R. W. 1969 *Planta* **88**, 261–273.
Fogg. G. E. 1968 *Photosynthesis* (Modern Biology Series). London: English Universities Press.
Fogg, G. E. 1975 In *Photosynthesis and productivity in different environments* (ed. J. P. Cooper), pp. 437–456. Cambridge University Press.
Gifford, R. M. 1975 *Solar energy progress in Australia and New Zealand* (ed. R. V. Dunkle), no. 14, pp. 15–18. International Solar Energy Society, A.N.Z. section, Melbourne.
Gifford, R. M. & Millington, R. J. 1975 *Commonwealth Scientific and Industrial Research Organization*, Australia. Bulletin no. 288.
Govindjee & Govindjee, R. 1975 In *Bioenergetics of photosynthesis* (ed. Govindjee), pp. 1–43. New York: Academic Press.
Harris, G. S. 1978 In *Alcohol fuels*. Institution of Chemical Engineers, Sydney, Australia.
Hatch, M. D. & Slack, C. R. 1970 *A. Rev. Pl. Physiol.* **21**, 141–162.
Kira, T. 1975 In *Photosynthesis and productivity in different environments* (ed. J. P. Cooper), pp. 5–40. Cambridge University Press.
Loomis, R. S. & Gerakis, P. A. 1975 In *Photosynthesis and productivity in different environments* (ed. J. P. Cooper), pp. 145–172. Cambridge University Press.
McCann, D. J. & Saddler, H. D. W. 1976 *Search* **7**, 17–23.
McCann, D. J., Saddler, H. D. W. & Prince, R. G. H. 1976 *Proceedings Annual Conf., Townsville, Institution of Engineers*, pp. 11–15. Australia.
National Development, Department of, Commonwealth of Australia (formerly Department of Minerals and Energy) 1974 *End use analysis of primary fuels; forecast* 1971–72 – 1984–85.
National Development, Department of, Commonwealth of Australia 1978 *Demand for primary fuels in Australia*, 1976–77 – 1986–87.
Ovington, J. D. 1968 *Aust. Forestry* **32**, 191–204.
Pimental, D., Nafus, D., Vergara, W., Papaj, D., Jaconetta, L., Wulfe, M., Olsvig, L., Frech, K., Loye, M. & Mendoza, E. 1978 *Bioscience* **28**, 376–382.
Platt, T. & Subba Rao, D. V. 1975 In *Photosynthesis and productivity in different environments* (ed. J. P. Cooper), pp. 249–280. Cambridge University Press.
Ryther, J. H. 1969 *Science, N.Y.* **166**, 72–79.
Saddler, H. D. W., McCann, D. J. & Pitman, M. G. 1976 *Aust. Forestry* **39**, 5–15.
Stewart, G. A. 1970 *J. Aust. Inst. agric. Sci.* **36**, 85–101.
Stewart, G. A., Gartside, G., Gifford, R. M., Nix, H., Rawlins, W. H. M. & Siemon, J. 1979 In *Potential for liquid fuels from agriculture and forestry in Australia*. Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia. (In the press.)

Discussion

M. W. Thring (*Department of Mechanical Engineering, Queen Mary College, Mile End Road, London E*1, *U.K.*). Dr Boardman has given figures for the replacement of the present use of petroleum in America and Australia by products from biomass and concluded that it will be very difficult to supply a petroleum substitute at the present rate of consumption. In my view, it is quite clear that, as petroleum becomes exhausted, we cannot possibly replace it at the same level of energy consumption, and that the provision of something like one-third of the amount of petroleum used at present in the developed countries will be quite sufficient to provide all our necessities. We have grown accustomed to the extravagant use because it was cheaply available, but it is nonsense to expect to continue this extravagant use when it is no longer available. For example, in my Department we are working on a diesel–electric hybrid four-seater car which we hope will give 100 miles/gallon (3.54×10^5 km/m^3). It will not, however, be able to accelerate to 100 miles/h (160 km/h) in a few seconds.

Yesterday, we heard from Mr Leach of the Building Research Establishment, that solar water heaters cannot possibly pay for themselves. However, at the moment the same applies to good agricultural land in East Anglia, and yet people are still finding it appropriate to invest in it. This land is fetching up to £2000 per acre, which is approximately \$1/m^2 and it is very difficult to grow the crops.

The biggest problem with biomass in England is that crops such as cereals only cover the land with green leaves for about three months in the year, so that they use only a fraction of the sunlight. There are several million tons of wheat straw and rape straw which represent a good energy source, but have no economic use in farming. To use them efficiently as a fuel, without excessive costs in collecting and handling, would be the most efficient use of sunlight in this country at the present time.

I had a letter from a farmer/engineer in Australia pointing out that if one had two horses to work one's land it would take two acres to feed them, whereas in Australia if one had a 2 h.p. (1.492 kW) cultivator, operated on alcohol from sugar cane and castor oil, it would only require 0.2 of an acre (0.81 ha) to run it, because one does not have to feed it all the time.

N. K. Boardman, F.R.S. I believe that Dr Thring is being very optimistic in predicting that about one-third of the present consumption of petroleum will be quite sufficient to meet the world's requirements. Even allowing for the current extravagant use of energy in the industrially developed countries of the world, and the scope for a considerable reduction in energy consumption in those countries, it seems unlikely that the total world energy requirements will fall significantly below the current level. Per capita energy consumption in the developing and underdeveloped countries is well below the average per capita world consumption and we must fully expect that it will rise considerably in those countries as development proceeds.

D. R. Johnston (*Forestry Commission*, *Forest Research Station*, *Alice Holt Lodge*, *Wrecclesham*, *Farnham*, *Surrey*, *U.K.*). At the present time the total world consumption of wood is about 2.5 km^3 per annum and this is obtained from about 2.5 Gha of productive forest. The demand for wood will inevitably increase in the future and is expected to double by the early decades of the next century. The World's forests are capable of producing several times the current yield, but this will not be obtained without new investment in planting, protection, roading, machinery, and education and training, and the real price of wood is more likely to rise than to remain constant or fall. It is not possible to say when woody material will be more valuable as a source of energy or as a chemical feedstock than as a source of timber or as a fibre for paper or board production. The relative values change with time as the relative values of energy and other wood based materials change, and they also change at a point in time from one region to another.

In countries with small reserves of fossil fuels but large land surfaces in relation to their populations, it may already be economic to use woody materials as a source of energy. In a country like Britain, however, woody material is unlikely ever to become an important energy source and for the foreseeable future most woody material is likely to be more valuable as timber or fibre than as a source of energy. Forest and industrial residues may, however, be exceptions to this, and it is also possible that some forms of fast growing wood-producing crops may locally become economic sources of energy. It is an advantage of such crops that they may be equally useful as a source of fibre, should this prove to be more valuable when they are harvested.

N. K. Boardman, F.R.S. I agree that, in Britain, forests are unlikely to become an important energy source, but I believe that an integrated approach should be used in planning and managing the forest resources of a country to make optimum use of forest materials for timber, fibre and energy.

D. T. Swift-Hook (*Central Electricity Research Laboratories, Kelvin Avenue, Leatherhead, Surrey*). Dr Boardman concentrated on fluid fuels from biomass but one-third of the energy in the U.K. comes from solid fuel. Current prices for sugar beet (expressed as £/GJ) are not much more than twice those for coal – we may be nearer than we think to shovelling sugar into our domestic and power station boilers if coal prices continue to rise! Unfortunately, the attractive figures are only for dry mass and drying is, I know, a serious problem. Power stations in Ireland sited on the edge of peat bogs have serious problems with de-watering, which can consume significant amounts of energy. Can Dr Boardman say what are costs the (in money and in energy), for crops such as sugar beet, of drying to produce solid fuel? Perhaps one attraction of converting to a fluid is that this must involve an effective method of drying.

N. K. Boardman, F.R.S. I agree with Professor Swift-Hook that crops compare unfavourably with coal as a solid combustible fuel. Freshly harvested plant material has a large water content, and it must be dried for combustion to be self-sustaining. I do not have energy and money costs of drying freshly harvested crops. Obviously, the most economical way is to utilize solar energy to dry the crop residues in the field before collection and transportation. On the other hand, conversion of biomass to liquid or gaseous fuels by the microbiological process of fermentation operates in an aqueous medium and is well suited to freshly harvested crops.