Bioenergetics of Tomorrow

PHOTOBIOLOGICAL ENERGY CONVERSION

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Introduction [1,2]

The process of photosynthesis supplies us with practically all our food, fuel and fibre. These products are derived directly from present day photosynthesis, or indirectly from fossil fuels which themselves are products of past photosynthesis and of course are not renewable. A better understanding of the mechanism of photosynthesis should enable us to realise its maximum potential in the future.

Photosynthesis is the conversion of solar energy into fixed energy: $CO_2 + H_2O \rightarrow$ organic material + O_2. This basic process was developed by the blue-green algae about 3×10^9 years ago and still remains our nearly sole source of fixed carbon and oxygen. The products of photosynthesis represent *stored* energy. Photosynthetic conversion efficiencies of 0.5% to 3% thus represent the efficiency of the total process; sunlight $\rightarrow$ fixed chemical energy. By contrast, for example, photovoltaic conversion efficiencies of 12–15% represent the process: sunlight $\rightarrow$ electric power, without including any energy storage.

Only fifty years or so ago CO_2 fixed in photosynthesis would have been used as food, fuel and fibre. However, now with abundant oil the products of present day photosynthesis are mainly used as food. We should re-examine and, if possible, re-employ the previous systems; but, with today's increased population and standard of living we cannot revert to old technology, but must invent new means of utilising present day photosynthesis more efficiently.

In this article we will deal briefly with a number of ways in which solar/biological systems could be utilised. The processes discussed could be realised to varying degrees over the short and long term. Some, such as the recycling of biological waste, use of leaf protein, and energy plantations, could be put into practice immediately, whereas others may never become practicable. Plant systems are diverse and adaptable; hence photobiological systems can be tailored to suit an individual country taking into consideration energy availability, local food and fibre production, ecological aspects, climate and land use. In all cases the total energy input (other than sunlight) into any biological system should be compared with the energy consumed in the construction of any other energy producing system.

Energy available [3,4]

Utilisation of the annual total radiation by the earth's plant life is only about 0.1% (3.2×10^{21} J of energy present in 2×10^{11} tonnes of carbon fixed per 3×10^{24} J of total radiation reaching the earth's surface in one year). Only about 0.5% of the fixed carbon is consumed as nutrient energy by the earth's 4×10^9 people (1.3×10^{19} J present in 8×10^8 tonnes of carbon consumed). This production of fixed carbon is however ten times the present world consumption of energy (3×10^{20} J in 1970). Thus the scope for increasing the total utilisation and for using photosynthesis in other ways is enormous – if we can improve yields, change crop types, harvest efficiently, decrease post-harvest deterioration, and so on.

Efficiency of photosynthesis [5–7]

Plants use radiation between 400 and 700 nm, the so-called photosynthetically-active radiation (P.A.R.). This P.A.R. comprises about 50% of the total sunlight which on the earth's surface has an intensity of about 800–1000 W/m² (5–6 J/cm²/min; also equivalent to 10^{-2} cal/cm²/sec or 42×10^4 ergs/cm²/sec for P.A.R.).

Table 1
Photosynthetic efficiency and energy losses [1,7,39,40]

	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, 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)[a] and 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 PS efficiency

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

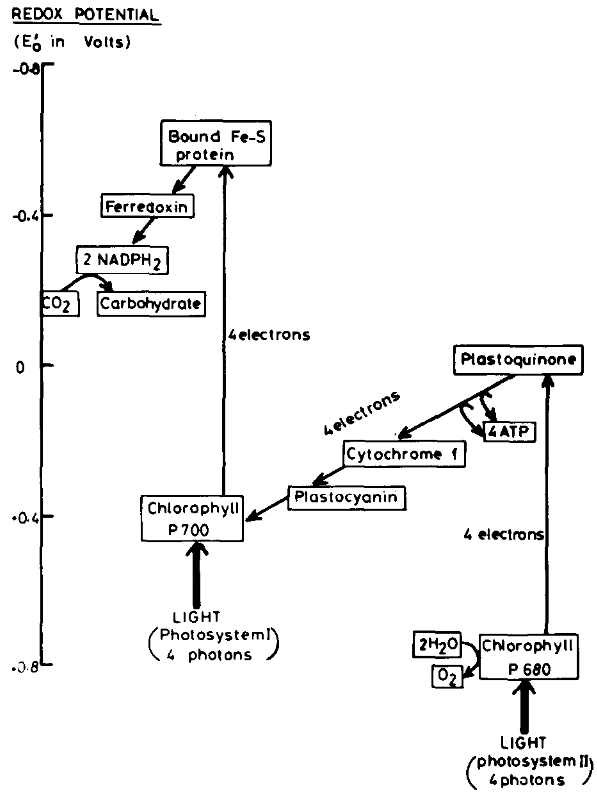

Fig.1. The photosynthetic electron transport scheme. One photon of light activates each electron at each photosystem. A minimum of 8 photons activate 4 electrons through the two photosystems to liberate one O_2 and fix one CO_2 [5].

The overall practical maximum efficiency of photosynthetic energy conversion is approximately 5–6% (table 1) and is derived from our knowledge of 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/mole of CO_2 and the 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 one mole of CO_2 is 0.47/0.176 = 2.7. However, since at least 8 quanta of light are required to transfer the four electrons from water to fix one CO_2 (fig.1), the theoretical maximum CO_2 fixation efficiency of light is 2.7/8 = 33%. This is for red light, and obviously for white light will be correspondingly less. Under optimum field conditions values between 3% and 5% conversion efficiency are achieved by plants; however, often these values are for short-term growth periods and when averaged over the whole year fall to between 1% and 3% (see tables 2 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%. Fig.2 shows the yields which can be expected under various sunlight intensities at different photosynthetic efficiencies.

Areas required for solar power

The proven primary energy resources of the Earth are equivalent to about 4.3×10^{22} J; this means that the solar energy annually reaching the Earth's surface (3×10^{24} J) is equivalent in about five days to our

Table 2
Some high short-term dry weight yields of crops and their short-term photosynthetic efficiencies. Data derived from [6,14,23,39–41]

Crop	Country	$g/m^2/day$	Photosynthetic efficiency (% of total radiation)
Temperate			
Tall fescue	UK	43	3.5
Rye-grass	UK	28	2.5
Cocksfoot	UK	40	3.3
Sugar beet	UK	31	4.3
Kale	UK	21	2.2
Barley	UK	23	1.8
Maize	UK	24	3.4
Wheat	Netherlands	18	1.7
Peas	Netherlands	20	1.9
Red clover	New Zealand	23	1.9
Maize	New Zealand	29	2.7
Maize	US, Kentucky	40	3.4
Sub-tropical			
Alfalfa	US, California	23	1.4
Potato	US, California	37	2.3
Pine	Australia	41	2.7
Cotton	US, Georgia	27	2.1
Rice	S. Australia	23	1.4
Sugar cane	US, Texas	31	2.8
Sudan grass	US, California	51	3.0
Maize	US, California	52	2.9
Algae	US, California	24	1.5
Tropical			
Cassava	Malaysia	18	2.0
Rice	Tanzania	17	1.7
Rice	Philippines	27	2.9
Palm oil	Malaysia (whole year)	11	1.4
Napier grass	El Salvador	39	4.2
Bullrush millet	Australia, NT	54	4.3
Sugar cane	Hawaii	37	3.8
Maize	Thailand	31	2.7

Other Yields: Loomis and Gerakis [40] discuss figures for (a) sunflower, growth rates of 79 to 104 $g/m^2/day$ have been reported, with a three week mean rate of 63.8 $g/m^2/day$ giving a photosynthetic efficiency of 7.5%, (b) carrot, growth rates of 146 $g/m^2/day$ and a dry matter yield of 54.5 tonnes/ha after 160 days were reported.

Note: Yields in $g/m^2/day$ can be converted to tonnes/ha/yr by multiplying by 3.65.

Table 3
Average-to-good annual yields of dry matter production. Data derived from [6,24,42]

	Tonnes/hectare/yr	$g/m^2/day$	Photosynthetic efficiency (percent of total radiation)
Tropical			
Napier grass	88	24	1.6
Sugar cane	66	18	1.2
Reed swamp	59	16	1.1
Annual crops	30	–	–
Perennial crops	75–80	–	–
Rain forest	35–50	–	–
Temperate (Europe)			
Perennial crops	29	8	1.0
Annual crops	22	6	0.8
Grassland	22	6	0.8
Evergreen forest	22	6	0.8
Deciduous forest	15	4	0.6
Savanna	11	3	–
Desert	1	0.3	0.02

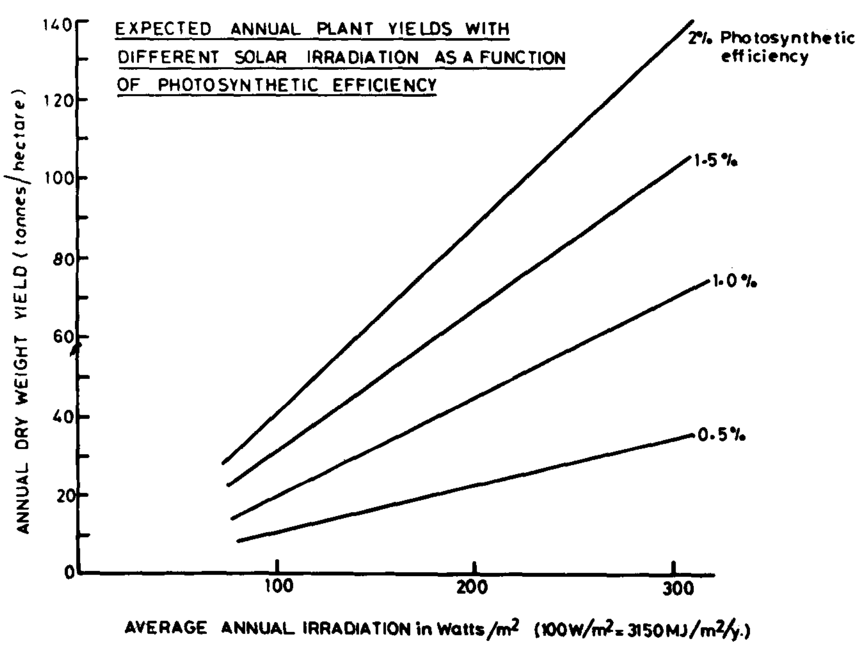

Fig.2. Expected annual plant yields as a function of annual solar irradiation at various photosynthetic efficiences [40,41,43].

Table 4
Land areas (approx. percent of total) required to provide total energy requirements (1970) from solar energy at a 10% conversion efficiency

Country	Area required
USA	1.5%
Australia	0.03%
UK	9%
France	3½%
W. Germany	9%
Denmark	4½%
Norway	½%
Sweden	¾%
Eire	1%
Netherlands	15%
Italy	4%
Spain	1%
Israel	2½%
South Africa	¼%

total proven energy resources, or is equivalent in about fifty minutes to the World's 1970 energy consumption (3×10^{20} J).

There are problems in collecting solar energy, the most obvious of which is its diffuse nature and the fact that it is intermittent; therefore any solar energy system has to have a storable component. If a 10% solar energy conversion efficiency was achieved (solar cells vary between 12% and 15% efficiency already) the land areas required in various countries to provide total energy requirements can be calculated (table 4). It is not implied that any country will ever achieve a complete solar energy economy, however, but shows the magnitude of the land areas involved. If the world could achieve say a quarter of its energy requirements through solar collection systems this would go a long way to solving the world's energy problems, both in developed and developing countries.

Food versus fuel [8–12]

The good agricultural efficiency achieved over the last thirty or more years has primarily been through the greater use of fossil fuels, e.g. the use of fertilisers such as nitrate, and mechanical operation systems. The following values show the comparative figures for the food energy output per unit of energy input: low intensity agriculture 20; intensive field crops 2; livestock production 0.2; greenhouse production 0.02. It has been calculated that for every calorie of food that we eat at our table it has taken 5 calories of energy to get in onto our plates – this is with a western standard of living. Most of these calories are inputs after the products have left the farm gate and include transport, packaging, retailing and cooking.

Calculations in the United States on energy output: input ratios in the production of maize grain have shown that this ratio has fallen from 3.7 in 1945 to 2.8 in 1970; that is a doubling of yield has been achieved by a trebling of energy input. In the UK where maize production is mostly for forage and the whole plant is considered, the output:input energy ratios usually are between 5 and 9. If the great use of nitrogen fertilisers (which often contribute 50% of the energy input) was decreased, e.g. by N_2 fixation or manure, considerable savings in energy could result.

The aim is to maximise energy output:input ratios. At the farm level we must be sure that we are not just converting oil into food without any net gain in energy, since it is the process of solar radiation via photosynthesis which increases energy output. Many of the agricultural systems which have been considered unprofitable in the past may now become more profitable due to the combined increased costs of food and fuel.

Leaf protein [13,14]

Leaves are potentially a large source of protein. Traditionally they are composted, discarded as waste, or fed to animals for conversion to meat, which is a very inefficient process.

Techniques have been developed by Pirie for the extraction of leaf protein which yield at the same time other useful products, namely fibre and soluble components such as carbohydrates, nitrogen and inorganic nutrient compounds. The composition of leaf protein is about 60–70% true protein, 20–30% lipid, 5–10% starch. Yields of two tonnes of dry extracted leaf protein per hectare have been obtained without irrigation and three tonnes can be expected. In the south-west US it has been proposed that if the yields of alfalfa (grown in an enclosed environment) reached that of sugar cane at 100 tonnes dry weight/

hectare/year, about 25 tonnes of protein could be extracted per hectare from alfalfa.

The choice of suitable crops for the extraction of leaf protein, fibre and other products should be carefully examined. Besides those crops usually considered (fodder crops, potatoes, sugar beet, and peas) consideration should also be given to perennial crops such as grasses and clovers, trees and bushes, and crops re-generating themselves making it economical to obtain a number of cuts in a given time. Additionally, both annual and perennial weeds, especially those species that start to grow early in the year despite low root temperatures, and that provide maximum year-round cover, may provide very good sources of leaf protein. Integrated approaches for using all possible leaf material, produced either as a by-product in conventional agriculture, or from plants grown specifically from such extraction, would seem to be of benefit in many countries of the world.

Energy plantations [4,15,16]

This implies the growing of plant materials for their fuel value, and is the only known operation that offers a renewable source of liquid fuels. Energy plantations may be considered as a long-term alternative to fossil and nuclear energy, providing us with the energy options we may require in the next century. They have been subject to feasibility studies in the US and Australia and the following advantages have been identified: (a) capable of storing energy for use at will; (b) renewable; (c) dependent on technology already available, with minimal capital input; (d) can be developed with our present manpower and material resources; (e) reasonably priced; (f) ecologically inoffensive and free of hazards other than fire risk.

Traditionally we think of energy plantations as forests, but increasingly we should consider alternatives, such as shrubs, weeds, agricultural crops, grasses, and algae (fresh-water and marine); for example, in Australia they have selected five species, namely *Eucalyptus*, Cassava, *Hibiscus*, Napier Grass and Sugar Cane as being potentially the most desirable high-yielding crops which can be harvested over the whole year. In the US one group has opted for fast-growing deciduous trees which re-sprout from stumps when cut (hybrid poplars). They calculate that at a 0.6% solar energy conversion efficiency with a rainfall of 38 cm or more per annum on non-arable land, about 1.2×10^4 hectares would be needed to fuel a medium-sized 400 MW electricity generating plant. In the Pacific a US Navy project is investigating the under-water farming of giant kelp beds. In the Republic of Ireland it has been estimated that they could provide their total primary energy requirements on 11% of their land area using crops operating at only a 1% photosynthetic efficiency. These energy crops would be grown on peat bogs which could be harvested on a continuous basis, so having a recurring energy source, rather than a once-and-for-all system as at present.

Cellulose [17,18]

This is probably the most abundant single organic compound on Earth (about 10^{11} tonnes are produced annually). It could be exploited as a source of energy, or food, or as a source of chemicals in the chemical industry. Technology for converting cellulose to glucose is now well advanced. This may be done with acid or alkaline treatment in order to break down the cellulose, but significant advances have been made in the utilisation of enzymes, or enzyme extracts from fungi, such as *Trichoderma* (fig.3). Good sources of cellulose are grasses, cereal straw, shrubs, trees etc. Another source is household refuse, which can contain 60% of its total weight as paper and vegetable material. It has been shown that one tonne of waste paper will produce about one half-tonne of glucose which could yield 250 litres of alcohol.

Waste disposal [19,20]

Many of the liquid and semi-solid wastes from our houses, industries and farms are ideal media for the growth of photosynthetic algae. Under good conditions rapid growth with about 3–5% solar conversion efficiency can be obtained. The harvested algae may be fed directly to animals, burnt to produce electricity, or fermented to produce methane. Simultaneously, waste can be disposed of and water purified; it is estimated that such algal systems are half to three-quarters as expensive as conventional waste disposal systems in California (fig.4).

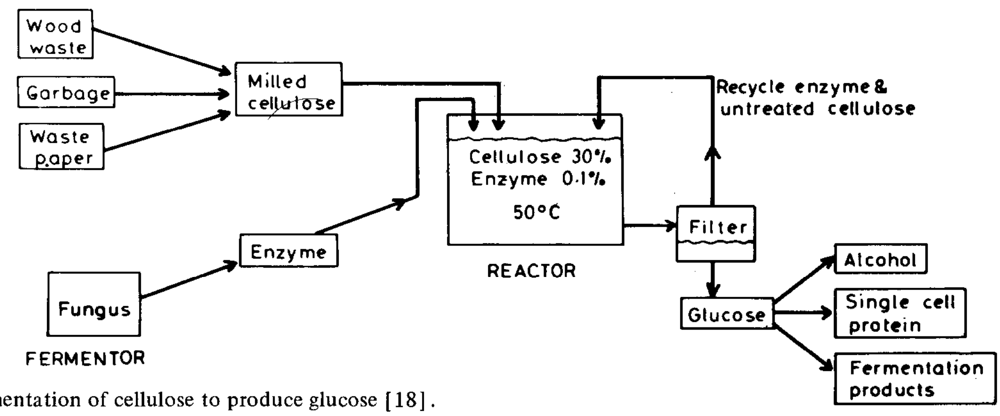

Fig.3. Fermentation of cellulose to produce glucose [18].

In California average yields of algae in excess of 100 kg dry wt/ha/day are obtained, with peak production in summer reaching three times this figure. Yields of 60 tonnes dry wt/ha/yr would produce 74 000 kW hours of electricity. Oswald has constructed algal ponds of 10^6 litres which give a 3% photosynthetic efficiency on a steady-state basis. In Napa, Cal., 120 ha of algal ponds on wasteland dispose of sewage from a city of 75 000 people. Large feeding systems for cattle and chickens have now been provided with algal ponds where the animal waste is fed directly into the ponds; about 40% of the nitrogen is recovered in the algae, which is subsequently re-fed to the animals. In 1974 Oswald calculated a cost of 3.85 US cents/kg algae; he estimated that growing algae in waste ponds could be competitive. He also calculates that 2 million ha of algal pond systems producing an average of 10 g/m^2/day could produce all the US protein requirements. The green algae presently grown have 50–60% protein but blue-green algae are being tried which contain 60–70% of extractable protein.

Greenhouse production [14,21]

This is often considered a very uneconomic process, except for specialist crops. However, utilising cheap and efficient greenhouse structures (the majority of greenhouses now used are very inefficient) may become feasible for a much larger and widespread production of ordinary crops. In addition, greenhouses could be used in cold climates, such as north Canada, and at the other extreme in the deserts of New Mexico and the Arab world. In cold climates greenhouses have been designed to reduce energy requirements by a third or more, using correct orientation, double layer glass or plastic, heat-absorbing walls and internal storage material, reflecting walls, roll-up shades, etc. Greatly increased yields and temperatures have been claimed. The possibility of using waste from power stations, etc. and of increasing the carbon dioxide concentration in the greenhouses will improve yields.

In the south-west US where photosynthesis efficiencies of 3% have been obtained with sugar cane outdoors, it is calculated that these efficiencies could easily be doubled under greenhouse conditions, utilising cheap plastic structures and hydroponic type fertiliser and water facilities. Such systems could be increasingly used in countries who wish to become self-sufficient agriculturally. There is also a large potential in temperate countries for greenhouse-type production which fulfill the requirements of maximum energy output for minimum energy input.

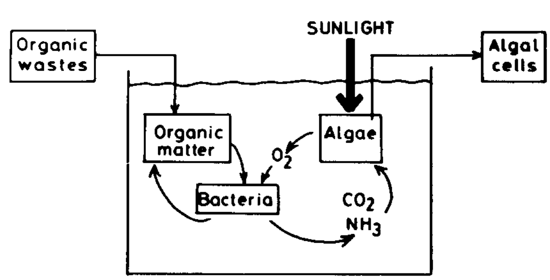

Fig.4. Production of algal biomass in an algal-bacterial pond [19].

Plant selection and breeding [22–27]

In order to obtain the maximum energy output from plants in a given area, photosynthesis needs to be optimised. Considering all or individually those factors which limit production, plants could be developed or selected that will give integrated maximum yields of food, fuel and fibre over the whole year.

The discovery of the C_4 pathway of photosynthesis, in which certain types of plants, e.g. maize, fix carbon dioxide into a C_4 compound as their initial product (instead of the conventional C_3 sugar which is normally formed by temperate plants, e.g. wheat) has given us a deeper understanding of the intricacies of photosynthesis. This discovery also led to the hypothesis that increased productivity might be achieved by manipulating plants to emulate some of the C_4 characteristics such as the efficient utilisation of low concentrations of CO_2, the ability to grow under water stress and high salt concentrations, and the ability to use intense light efficiently. It has also been suggested that the process of photorespiration *may* decrease yields by up to 50%. This loss arises from the recycling of the photosynthetically fixed carbon in the plant so as to re-evolve CO_2 which is thus lost from the plant. Utilising our knowledge of C_4 characteristics of plants and of photorespiration *may* allow the breeding and selection of efficient photosynthetic plants. Chollet and Ogren put it strongly. 'The control of this process (photorespiration) and the associated oxygen inhibition of photosynthesis has emerged as representing one of the most promising avenues for dramatically increasing the world supply of food and fibre'.

Genetic engineering using plant cell tissue cultures is a recently developed technique which has great promise for improving plants. Species and genus crossings and creation of new hybrids by mutations induced in the cultures are possible. There seems little doubt that these cell culture techniques may ultimately become routine tools in the difficult task of plant improvement, greatly increasing the scope of plant breeders.

Regulation of plant reactions and products [28–30]

Usually crops are grown for one final product, such as grain or root, containing constant proportions of carbohydrate, protein and fats. The possibility exists that we could alter biochemical reactions at defined times during the growing season in order to obtain more or less of a given constituent. It is also possible that we could regulate detrimental processes in the plant, such as photorespiration and water losses, giving greater net plant yields. There is some work on algae but whole plant systems should be investigated.

A well-known whole plant system is that of the regulation of photorespiration. In some C_3 species the release of photorespiratory CO_2 may be three- to five-times greater than that released by dark respiration. This is in contrast to C_4 plants which have very low rates of photorespiration. Three compounds which are thought to block photorespiration have been recognised and it is proposed that they could increase photosynthetic efficiencies by up to 50%. These experiments are still not at a field scale, but may show some promise for the future. Even though this is a scientifically controversial field the advantages of slowing photorespiration by biochemical or genetic means are great.

The possibility of regulation of the final products of carbon dioxide fixation in plants also deserves consideration. Work in some industrial laboratories shows that certain plant products, such as sugar, starch and lipids can be used in the production of many different products, such as detergents and plastics. In these cases the plant is operating as an intermediate CO_2-fixation apparatus, whose continuously renewable product is used in the chemical industry.

Nitrogen fixation [31,32]

It is thought that one of the major limitations, of N_2 fixing capability in both symbiotic and associative symbiotic systems is an inadequate supply of carbohydrate to the N_2 fixing bacteria; more efficient photosynthesis could overcome some of these problems. The very interesting discovery of associative symbiotic N_2 fixation in grasses such as maize (and possibly wheat and rice) has led to the realisation that improved carbohydrate production may be the prerequisite for useful extension of biological N_2 fixation to other crops.

When soya beans are grown under greenhouse conditions, a 3-fold increase in CO_2 concentration in the atmosphere resulted in a 6-fold increase in the amount of N_2 fixed/ha; yields increased from 75 to 425 kg of fixed N_2/ha. CO_2-enriched soyabeans fixed 85% of their N_2 requirement, whereas the unenriched plants fixed only 25%, obtaining the rest from the soil in the form of nitrate fertilisers. It is possible that this increased net production of photosynthesis, and hence N_2 fixation, is made possible by a decrease in photorespiration due to the increased CO_2 concentration in the atmosphere.

Biocatalytic hydrogen production systems [33–36]

There is a direct interest in both living and non-living systems which emulate the biological production of H_2 gas via the breakdown of water (fig.5). Certain algae produce H_2 gas under specific conditions and contain the enzyme hydrogenase. Thus with a hydrogenase any plant type system could have the ability to produce H_2 gas. This has been demonstrated in the laboratory using components extracted from leaves and bacteria. The ultimate object should probably be to use a completely synthetic system mimicking the algal or plant-bacterial systems. In this case an Fe–S catalyst would be used instead of a hydrogenase, a chlorophyll layer membrane instead of the chloroplast, and a manganese catalyst to evolve the O_2 from H_2O. A two-phase system has been constructed where O_2 is evolved in the light and H_2 in the dark; or a single-phase system where H_2 and O_2 are evolved simultaneously and then separated by semi-permeable membranes (or even possibly burnt directly). There are problems of stability in the living systems which would need to be overcome before any biological based system could be practical. Recently this system has been shown to operate on a continuous basis for six hours or more.

A preliminary economic assessment of this type of system has been performed, assuming a 10% energy conversion efficiency. The conclusion was that in the south-west US deserts 9 moles of H_2 could be produced per m^2/ day and 130 km^2 of such collectors could produce 2500 tonnes of hydrogen per day, possibly using sea water as the source of water and coolant. It was considered that this photosynthetic system could complete very favourably with similarly-located solar thermal energy systems. However, these conclusions are very tenuous because of our inability so far to produce H_2 gas on a continuous, long-term basis.

The biocatalytic hydrogen production system is attractive because it involves the use of unlimited supplies of energy (the Sun) and substrate (Water) to produce a storable and non-polluting energy source (H_2 gas).

Carbon reduction [2,37]

In vitro systems which emulate the plant's ability to reduce CO_2 to the level of carbohydrate are a very attractive proposition and are being actively investigated by biochemists and synthetic chemists. A recent report claims the formation from CO_2 of keto-acids (and then amino acids) using an alkyl-mercaptan, an Fe–S protein analogue, and an inorganic reductant.

It may be possible to induce plant systems to

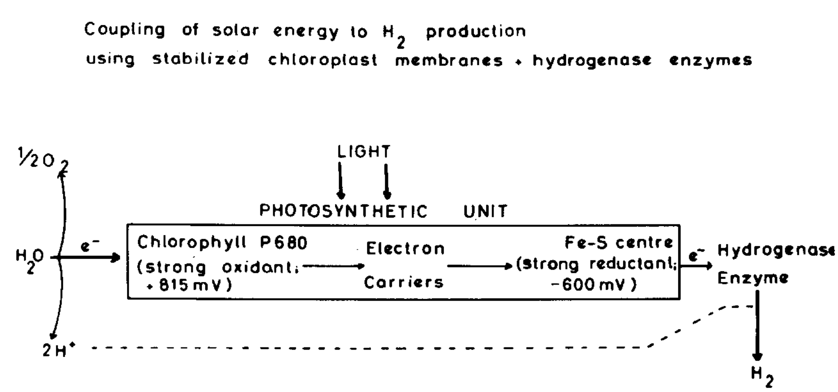

Fig.5. The coupling of solar energy to hydrogen production [36].

reduce carbon to the level of carbohydrate on a continuous basis to produce compounds such as glycolate or formate, instead of carrying out the normal transformation of carbohydrate into other compounds like protein and fats. Algae are known to produce glycolate externally under certain conditions and thus could possibly be used in such a system. A more speculative possibility would be to use the plant's ability to produce light-induced energy-rich reducing potentials at −600 mV in Photosystem I; this could be done via coupled enzyme or catalytic systems to produce fixed carbon compounds. The reducing potential is there and just needs to be coupled to carbon fixation.

Artificial chlorophyll membranes [2,38]

The chlorophyll-containing membranes of all photosynthetic organisms are able to separate positive and negative charges on either side of the membrane under the influence of light. This basic photogalvanic system is a key to photosynthesis which we might be able to use directly for the production of electricity or the storage of energy. Artificial chlorophyll-containing membrane bilayers have been used and shown to produce currents and charge separation. The possibility of utilising such artificial membranes or vesicle structures for direct photochemical systems has scope, even though the efficiencies so far achieved are very low.

Concluding remarks

Photosynthesis is a 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 from both energy and food points of view. Their applicability might be immediate in some tropical areas and countries with large amounts of sunshine. However, in more temperate climates there is still a large potential for the utilisation of the ever-abundant solar energy. We in Europe should not consider that we do not have sufficient solar energy. The difference in total annual solar radiation between the UK and Australia or the US is only a factor of 2. The difference between the UK and the Red Sea area (the area with the most amount of solar energy in the world) is only a factor of 3. Whatever solar energy systems are developed, these could provide viable alternatives to other types of energy production in the next century. Whatever systems are devised in the temperate zones could be applicable to those countries that have more sunshine and these are predominantly the developing countries of the world. Thus the temperate countries could help themselves by becoming self-sufficient and help the other countries of the world by not competing for their food and raw material. Lastly, we might have an alternative way of providing ourselves with food and fuel in the next century and we should consider all our energy options and not put all our eggs in one basket (nuclear or otherwise).

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[1] This article is in part derived from Chapter 9 'Agricultural & Biological Systems' of a Report entitled 'Solar Energy: a United Kingdom assessment' published May 1976 by the UK Section of the International Solar Energy Society, 21 Albermarle Street, London W1. The members of the Working Group for Chapter 9 were Brown, H., Chittenden, A. E., Coombs, J., Hall, D. O., Pirie, N. W., Walker, D. A. and Warren-Wilson, J., whom I thank for their significant contributions and collaboration. The author's previous endeavour along these lines was published in 'Sun at Work in Britain' (1974) Vol. 1, pp. 14–17 UK Section ISES.

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