Solar Energy in the Nineteen Eighties*

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ABSTRACT

Solar energy is abundant, inexhaustible and nonpolluting. Its utilization does not affect the climate, and it does not lend itself to military applications. The solar-thermal, solar-electric and solar-chemical options are available.

The production of low-temperature heat for warm water and for space heating, of enormous importance in the energy budget, is economic already now in many situations. Technical progress is still considerable. With the further rise in fuel prices the application will increase dramatically.

Use of solar heat for large-scale generation of electricity, i.e. of power on the basis of the solar-thermal option, should be approached cautiously. Possibilities include the tower concept and ocean thermal-electric conversion (OTEC). Investment would be large, and the technology hard. Better long-term chances may be given, for decentralized application in developing countries, to the farm concept.

In contrast, the chances for cheap small-scale, and later large-scale, use of solar semiconductor cells (solar-electric option) are most favourable. Technical progress is rapid, and prices drop precipitously.

For the production of fuel, the solar-chemical option is in the foreground. Gaseous, liquid and convenient solid fuels can be obtained from biomass, especially by fermentation. At the moment, biogenic wastes are already available in relatively large amounts. Subsequently, energy farming is to be introduced. Biomass converted to hydrogen can be employed for production of electricity by means of fuel cells.

In the more distant future, hydrogen is to be made abiotically by photolysis of water, and is to be introduced into a hydrogen economy. Probably the technology will be based on the application of synthetic membranes.

It is possible that regenerative solar energy in all its forms can in the end replace all existing energy used by man. This substitution will, however, be a gradual process.

1. INTRODUCTION

Solar energy has been inherited by mankind from its ancestors in evolution (1). All energy utilized by them was ultimately derived from sunlight. It was *J.R.Mayer*, the discoverer of the Law of the Conservation of Energy, the First Law of Thermodynamics, who in 1845 stated that photosynthetic organisms need light for energy. Until recently all energy used by man was likewise ultimately solar energy. Much of it was, of course, fossilized: coal, oil gas. But for the purpose of this paper we shall mean by solar energy only the energy that comes to Earth currently.

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Solar energy has only beneficial aspects. It is inexhaustible, its use does not greatly affect the climate or lead to chemical or radioactive pollution, and it hardly lends itself to military applications on any scale, although Archimedes is reported to have set fire to enemy ships by concentrated sunlight. However, the problems of the availability and the economics of solar energy remain to be examined.

Solar energy is basically more natural than nuclear energy as it involves only forces to which the organisms could adapt themselves during the 4 gigayears (milliard years) or so of their existence (1). In contrast, up to our time living beings never had to face high intensities of ionizing radiations, and therefore they could not evolve mechanisms of protection against them. Nor did they learn to resist the blast or heat from nuclear explosions !

In this paper, the problems of nuclear energy will not be dealt with. It will rather be assumed that for a number of reasons man has decided to get away from nuclear energy. In my view, the most serious reason is the proliferation of the capacity to make plutonium, the material for nuclear weapons (2). A survey on the effects of nuclear weapons can be asked for (3).

As the importance of solar energy is increasingly recognized in many countries, literature is also growing exponentially. In particular, many fine books are being published. May the author, as an Austrian, here just mention one very good first introduction (4), written by one of the Directors of the partly State-owned Austrian Solar Energy and Space Research, ASSA. ASSA has also been organizing interesting symposia and has published their Proceedings, e.g. (5).

2. GENERAL ASPECTS

The amount of carbon in exploitable fossil fuel, already discovered or still to be discovered (!), is estimated by the leading expert *K. Hubbert* at about 8×10^{12} (8 European billion) tons (1). It is mostly coal. If it were crudely assumed, to get the order of magnitude, that the fossil fuel was laid down during, say, 1 gigayear, we are consuming now each year, at the present rate of overall consumption of 5 milliard tons of carbon per year, what Nature produced during half a million years. Alternatively it can be stated that the resources, if used fully at the present rate, will last for 1000-2000 years. In reality, the rate of consumption shows, as is well known, a sharp upward trend.

However, for various reasons this trend cannot be allowed to continue long. First, a tolerable limit must be set to the carbon dioxide content of the atmosphere. Secondly, an important increase in coal mining would affect the environment very badly, and would also sentence enormous numbers of fellow humans to a life in the darkness of the coal mines. A strong increase in oil or gas production is clearly impossible in any case.

While the resources of fossil fuels are subject to exhaustion, and moreover it may not be possible to exploit them fully, the flux of solar energy is both enormous and practically everlasting. All the time 170 billion (170×10^{12}) kilowatts reach the top of our atmosphere. This corresponds to about 40,000 kW per head of the world population. One half of this penetrates to ground level. We compare with present consumption of energy in all forms: about 11 kW per head in USA, 4 kW in Europe, 2 kW in the world, and 0.2 kW in South Asia. Therefore a tiny part of this energy would cover all reasonable energy needs of mankind.

The resources of fossil fuel represent the energy equivalent of the total solar radiation that comes to the Earth during a fortnight only. As the carbon in the yearly products of plant photosynthesis ("photosynthate") is about 10^{11} tons (1), the fossil fuel is equivalent to the photosynthate during 80 years. Thus a minute fraction only of the solar energy (about $10^{-7}\%$) has been stored during the 4.7 gigayears of the existence of the Earth. The bulk of the energy was re-emitted into space in the form of dark (infrared) heat radiation. For convenience, the orders of magnitude, as estimated by *Revelle* and *Fairbridge*, are shown in Table 1 (1). Needless to say that estimates by different authors differ greatly.

Table 1. Amounts of reduced carbon (10^9 tons).

All reduced carbon in sedimentary rocks	6,800,000
Exploitable fossil fuel	8,000
Existing biomass (living)	90
Existing biomass (dead; on land mostly timber)	3,500
Annual photosynthate	100

Solar energy is not only abundant, it is also of high quality (6). Its energetic potential is high. Thermodynamically, direct solar radiation can be ascribed the very high temperature of its source, i.e. the visible surface layer of the Sun, about 6000 kelvins. Therefore sunlight is characterized by a low content of entropy per unit content of energy. As entropy is a measure for incapacitated energy, we conclude that solar energy, at its high temperature, is eminently suitable for doing work. According to the famous equation of *Sadi Carnot*, valid universally, of the energy of heat that flows from a higher level of 6000 K to a lower level of 300 K (temperature of the terrestrial environment), 95% can in principle be converted into useful work. The temperature of scattered sunlight is less (6). According to *Spanner*, it may in practice be 1350 K - still fairly high (6).

The Carnot equation can be applied to the work done in photosynthesis. This fact has been expressed in 1886 in powerful words by the great physicist *Ludwig Boltzmann* (7,8), to whom we owe the interpretation of the Second Law of Thermodynamics:

> "Therefore the general struggle of the organisms is not a struggle for the elements, nor for energy, which is present in large amounts in every body in the form of heat, unfortunately unchangeable, but the struggle for entropy, which becomes available in the transition from the hot Sun to the cold Earth. To exploit this transition as far as possible, the plants spread out the immeasurable areas of their leaves and force solar energy in a manner as yet unexplored, until it sinks down to the temperature level of the surface of the Earth, to carry out chemical syntheses of which we have no inkling as yet in our laboratories. The products of this chemical kitchen are then the object of the struggles of the animal world."

On the other hand, solar energy has its specific difficulties. They are:

1. Unequal distribution over the globe. This problem is, however, less acute than is often thought. E.g. the solar energy income per unit area at ground level in temperate Europe still is one half of the maximum income, in the Sahara. In any case, other energy sources are also unequally distributed between countries.

2. Intermittency. Dark or cloudy periods must be bridged over. This is possible either by energy storage or by backup through energy from other sources.

3. Dilution. With vertical incidence, the total flux is only about 1.4 kW at the top of the atmosphere. At the actual angle of incidence and at ground level, a typical average value in temperate Europe is one tenth. This corresponds to 140 MW (thermal) per km^2.

4. Loss of directionality. Only the direct sunlight can be concentrated by means of lenses or mirrors. In some applications, such concentration is needed.

We shall deal with the problems resulting from the difficulties as they arise.

3. THREE OPTIONS FOR SOLAR ENERGY

It is convenient to distinguish three basic options for the utilization of solar energy, the solar-thermal, the solar-electric and the solar-chemical option. Here the primary process serves as the criterion. Thus the possibility remains, e.g., to use the solar-thermal option, in a subsequent step, for the production of electricity.

A) The solar-thermal option

a) Low temperature: hot water production and space heating

Sunlight can give heat at low, at intermediate and at high temperatures. The methods for low temperatures (hot water production and room heating) are well developed already (4), but nevertheless further great technical progress is expected. The collectors as well as the circulation and storage systems are still capable of drastic improvements. For low-temperature devices concentrators for the radiation are seldom used, but for intermediate or high temperatures they are indispensable.

The importance of low temperature heat is enormous. For instance in Austria about 40% of all primary energy is used for warm water production and space heating (4). Of course, the energy needed could be much reduced, here and elsewhere, by conservation measures.

In Austria, it has been reported by industrial engineers in a meeting held by ASSA in May, 1979, that already more than a thousand houses have solar heat installations. In many situations in this country, a cover of 70% of the hot water requirements is economic already at existing prices of equipment and fuel. It is anticipated that through further development work house heating will begin to be economic by 1982. Heat for large stables, where temperatures need not be so high, could be even cheaper. Further we must keep in mind that fuel prices will continue to rise. In the USA, the number of houses equipped with solar installations has doubled every 8 months since 1973 (9), and probably by 1985 no less than 2.5 million homes will use solar heat (9).

The main obstacles in the way of even more rapid progress everywhere are partly technical-organizational, and partly fiscal-economic (10). Designs have not yet been fully optimized so that people feel that next year they can make even better bargains. Moreover the supply of builders and plumbers skilled in this field is limited.

Further, the tax and price structure do not yet take solar energy into account (10). Thus in the USA the pricing of oil and gas, controlled by the Government, is not based on the costs of new supplies, but on average costs of production. In income tax, fuel cost, but not finance of solar heating equipment, is deductible; this clearly leads to unjustified advantages for fuel. Nevertheless it has been concluded (10): "Even without federal incentives some solar water and space heating systems are (already, E.B.) competitive. Enactment of the solar tax credit, however, greatly enhances their competitiveness." The relevant legislation is under way.

A transition to higher percentages in the cover of the needs or even to houses fully heated by sunlight would require disproportionally larger investment. Obviously in most situations a backup of the solar heating systems by a system for burning fuel is needed. But this latter system will be used less and less as methods for the storage of heat are improved. The need for backup heat varies not only between situations but also between fields of application. In hotels etc., that are visited in summer only the need is small, and in open-air swimming pools it may be zero (4). In these circumstances it is dismaying to see that even in warm countries like Dalmatia or Spain - no indigenous fuel resources! - hardly any hotels are equipped as yet to use sunlight. This is unforgivable.

The energy may be stored at increased temperature, as sensible heat of water, gravel, etc., or as latent heat in hydrates, etc. Clearly good thermal insulation is crucial. Scaling offers enormous advantages in costs of installation and of operation both for the solar and the backup system. The study of storage may be most advanced in Sweden, where experimentally hundreds of houses are linked for community storage (11,12).

The prices of heat pumps have decreased greatly in recent years (5). As soon as they are cheap enough they can be used to pump heat, obtained by sunlight at a low level of temperature during relatively cool periods, to a higher temperature level. Heat pumps can also be applied to the heat in waste water from industry etc., and even of domestic waste water, especially from multitenement buildings.

A special field of application of solar heat is the drying of farm products, including grain, hay and clover (4). Further we note in passing that in hot countries cooling and climatization by solar energy, essentially through the use of reversed heat pumps, will become enormously important. Further, solar cookers are used increasingly in the hot parts of the world. Desalination of sea water is another task in hot countries.

b) Intermediate temperature: electric power

ba) Tower concept

The direct solar radiation is reflected by a large number of inclined mirrors that follow the sun, and is concentrated on a central receiver on top of a tower (13, 14). In the receiver water is boiled, and the steam drives a turbine coupled to a generator for the production of electricity. A pilot plant, without generator, already exists in Albuquerque, USA. The tower is 60 m high, and 500 kW of heat are produced. In Barstow, USA, a further plant has been under construction since 1978. It will supply up to 10,000 kW (kW (e)) of electric power. A commercial plant with a tower of 300 m and 10,000 mirrors 37 m^2 each is supposed to supply 100 MW of electric power in the nineties.

The present author has his doubts about this prospect at hard technology and highly centralized power production. Investment will be enormous, and maintenance difficult. The problems of intermittency of sunlight, with the resulting strain on materials, and of storage will be very considerable indeed.

bb) Farm concept

The basic principle (14) is similar to that of the tower concept, but the plant may, presumably at the expense of thermodynamic efficiency, be simpler, cheaper and better adapted to varying conditions. There is no central receiver, and the radiation is reflected by curved mirrors to a network of pipes filled with a liquid where the vapour is raised. As the temperature reached is not so high, freon rather than water may be used as working substance.

Power stations of, say, 50 kW (e) may be useful for hot countries without an electric grid. The current would e.g. provide light to a village and would pump drinkwater for people and animals. Radio and television would become available even to illiterates, who up to now know very little about the world. The social value of such service would clearly be enormous compared to financial investment. (This would also apply to solar cells - see below). The power would, however, not be enough for heating, cooking, mechanical work or irrigation on any scale. A pilot plant of 10 kW (e) has been built (15) in the research centre of Seibersdorf, Austria, and a plant of 500 kW (e) is under construction by an international effort near Almeria, Spain, side by side with a tower power plant of similar size (16).

bc) OTEC concept

It is convenient to mention this concept here although all temperatures involved are low. The difference in temperature between the deeper layers and the surface layers of the ocean in the tropics is intended to be used (9) for power generation by means of a low-boiling working medium (Ocean Thermal-Electric Conversion-OTEC). Intermittency or storage are no problems, but because of the smallness of the temperature difference thermodynamical efficiencies of some 2% only can be expected. Such plants, maybe 200 MW (e), could be placed on floating platforms, but the transport of the energy will then be a great problem. It has been suggested to make electrolytic hydrogen gas and to react this with atmospheric nitrogen to give ammonia. Clearly such processes need enormous investment, and the losses in operation will also be large.

c) High temperature: solar furnace

In solar furnaces the sunlight is concentrated by mirrors sufficiently that in a relatively small volume temperatures of thousands of degrees, say 4000°C, are reached. The classic example is the plant in Odeillo in the French Pyrenees.

This fine achievement demonstrates that indeed the direct solar radiation has maintained the temperature of the source, as pointed out before; otherwise it would be impossible to reach near-solar temperatures. Plants of this kind cannot be used for the practical generation of electricity, but they are useful scientifically, especially for the study, the treatment and the testing of materials.

B) The solar-electric option (solar cells)

Although most R & D in the utilization of solar energy by semi-conductors since the introduction of the "solar cells" by Bell Laboratories in 1954 has been carried out by a handful of workers in small laboratories, progress has been staggering. The prices have fallen at a precipitous rate, and many authors foresee that eventually the price drop may be similar to that of that other semiconductor device, the transistor. Among the main lines of development we may mention the following (17,18,19).

Cheaper silicon monocrystals are being made available. The aim of the U.S. Federal Low Cost Silicon Project, managed by the Jet Propulsion Laboratory of the University of California, is to reduce the price of purest Si, per kg, from 65 to 10 dollars. Methods for the growth of single crystals are also to be improved. The wastage in the preparation of the wafers, now 80%, is to be cut. The arrays of cells on their panels are to be put together by automatic methods. Generally the share of hand labour is to be radically diminished.

The possibilities of the replacement of single crystal of Si by films of polycrystalline or even amorphous (20) Si are being studied. The production in ribbon form, so that no sawing is needed, is attempted. In one promising process, the West German *Fischer* process, thin polycrystalline films of Si are made by action of electric discharges on silicon hydride gas, doped by phosphorus hydride, etc. For thin cells on the basis of amorphous Si, perhaps only 1% as much Si may be needed as for the present commercial cells. Thin films have good flexibility, they are resistant to ionizing radiation, and their action spectrum matches the solar spectrum well. In a different line of work, thin films of various insulators or semiconductors are "cosputtered" with transition metals, and their properties thereby modified. Here quite a new field has been opened up again (21).

Among solar cells consisting of two different materials, i.e. the "heterojunction" cells, copper sulphide/cadmium sulphide cells (14) are in production already. The thin, polycrystalline, films may be obtained cheaply in an automatic process by spraying the sulphides successively on rapidly moving hot glass. The target is a price of 5-15 cents/peak watt, i.e. per watt in full sunshine, against more than 10 dollars in present commercial solar cells. An unsolved problem consists in the relatively poor chemical stability of the system. This drawback disappears if the copper sulphide is replaced by indium phosphide.

The action spectrum of thin, polycrystalline, gallium arsenide films fits the solar spectrum ideally. The cells are made in well established techniques through epitaxial growth, i.e. the material deposited from a gas or a solution adapts to the crystal structure of the support. GaAs is particularly heat resistant and is therefore well suited to application of concentrators, where the sunlight is caught by mirrors or lenses. The concentrated sunlight gives correspondingly higher energy yields, but suntracking is needed. Cooling of the arrays is also required. This adds to the costs, but the heat carried away, at fairly high temperature, can also be useful ("cogeneration"); for instance, absorption air-conditioners may be run with it. 2000-fold concentration has been reported (17), still with 19% efficiency; in this case, the current is tens of amperes per cm^2, and the flow of heat energy 4 times larger still. GaAs is expensive, but need not remain so. Both components, Ga and As, are abundant in Nature.

Solar-electric installations are especially promising for developing countries which lack utility grids. They want decentralized power sources that can be built up from modules. Another advantage precisely for these countries is that no specialist or expensive maintenance is required. Moreover, the developing countries often have a lot of sunshine.

According to *Kelly* (18) and the report of the *Ehrenreich* committee specially set up by the American Physical Society (22) there is little doubt that within 3-5 years the cost of electricity from solar cells will go down by a factor 5 or so, namely, from 11 to 1 or 2 dollars/peak watt. The price of 11 dollars/W practically corresponds (presumably in USA) to 1-2 dollars per kWh. The goal set in 1977 by ERDA, the Energy Research and Development Agency, is 2 dollars/W in 1982, 0.50 in 1986, and 0.1 - 0.3 in the nineties (18). For comparison: even in capital cities of developing countries prices of 0.20 - 0.25 dollars per kWh are common now (18), if electricity can be supplied at all!

Beyond the level given considerable further engineering work will be needed. Moreover, the noncell costs increase percentagewise, especially for the production of the arrays, for auxiliary equipment and for land, as the costs of the cell themselves go down. In Table 2 some technical data (18) are compiled. Note that diffuse as well as direct sunlight is utilized, provided no concentrators are applied.

Table 2. Photovoltaic cell efficiencies (%).

Device	Maximum	Actually measured	Commercially provided
Silicon single crystal	20 - 22	19	10 - 13
Silicon polycrystal	?	7 - 14	-
Cadmium sulphide/ copper sulphide	15	8	2 - 3
Gallium arsenide	25 - 28	15	-

Forecasts for the size of the market as a function of the price reached are also available (Table 3). Note that prices refer to arrays rather than cells. Obviously, the estimates differ greatly. Also it is not clear whether the figures refer to the USA or the world. In 1976, the total sales were only 0.38 megawatts, but the future of the solar cell is bright indeed.

Table 3. Market size as a function of array price (megawatts annual sales).

	Estimate by		
Dollars/peak watt	Department of Energy	Texas Instruments	Radio Corporation of America
10	1	0.4	0.8
3	8	2.6	13
1	75	30	200
0.5	500	100	2,000
0.1-0.3	5,000	20,000	100,000

C) The solar-chemical option

ca) Hydrogen economy

It is fitting to begin with a tribute to the genius of *Albert Einstein* whose 100th birthday was celebrated all over the world in 1979. In his momentous paper in 1905, in which he put forward the hypothesis that light consists of energy packets, quanta, he also showed that the capacity for photochemical reactions does not depend on the dilution of light. As light spreads, the number of quanta per unit volume, but not their quality (energy), decreases. Hence dilute sunlight gives the same photochemical reactions as concentrated sunlight;

merely the rates of the reactions are less. As with solar cells, diffuse as well as direct sunlight can be exploited.

The energy of the light must be stored in the products of reactions that require input of energy, of "endergonic" reactions. The most obvious possibility is the splitting of water into its components, hydrogen and oxygen. This "photolysis" of water is analogous to its "electrolysis". The hydrogen obtained can be fed into a "hydrogen economy", which has already been studied in different contexts (23). Hydrogen is easily stored and transported. It can be used for low-temperature or high-temperature heat, instead of coal or coke in metallurgy, and as a reactant in chemical industry, e.g. for the reduction of practically worthless carbon dioxide to methanol or hydrocarbons. Hydrogen gas can even be fed to certain ("Knallgas") bacteria whose biomass may thereafter be used as feedstuff or food.

Great interest is also presented by electricity production in a hydrogen economy. Clearly this is possible through hydrogen-powered heat engines, though the Carnot factor leads to large losses. No loss of this kind need be suffered if fuel cells rather than heat engines are used.

Commercial use of fuel cells is imminent in USA (24). At the moment, the hydrogen is obtained from other sources than photolysis, namely, from the conversion of fossil fuels. According to the "TARGET" project, sponsored mostly by gas utilities, 50 stations, 40 kW (e) each, will be tested during 1979-1981, and such stations should be commercial in 1982. Moreover the FCG organization of the electric utilities is setting up a plant of 4500 kW in downtown New York to be operational in 1980. The cells use phosphoric acid as electrolyte, work at 150 - 200°C, and require small amounts of platinum as catalyst. The fuel processors that precede the cells and make the fuel, H_2, accept gas, naphtha or coal. Energy efficiency is, for the time being, 35 - 40 %. With a delay of 5 - 10 years cells may be introduced that use molten carbonate, operate at far higher temperatures, need no catalyst and are hoped to have 45 - 47 % energy efficiency.

The endurance aimed at is 40,000 hours. Future large power stations are meant to be used either for base load or for load following. Economic work will be possible as soon as capital outlay is reduced to 350 dollars/kW. The needed outlay, in turn, will depend steeply on extent of application.

cb) Photolysis of water

Work on the photochemical utilization of solar energy in man-made systems is being done on an increasing scale, but no real success has so far been obtained (25,26,27). This applies also to the photolysis of water, notwithstanding the fact that the energy of the quanta at least of green, blue and violet light is theoretically sufficient for water splitting. The lack of success is clearly due to the fact that in the action of light the primary products do not consist of the stable gases H_2 and O_2, but of reactive intermediates. In ordinary, homogeneous, systems (water or solutions in water) the reactive particles collide rapidly and recombine, thereby re-forming water.

To prevent these harmful back-reactions, it has been suggested to apply the "membrane principle" (28,29,30). The primary photochemical reaction is to be carried out not as a "scalar", but as a "vectorial" reaction, where the different reaction products are emitted into different directions, thereby separated, and prevented from meeting again. For such vectorial reactions, asymmetry of the photochemical system is a necessary, but not a sufficient condition. In practice, the system will consist of a membrane with asymmetric structure, into which the light-absorbing photocatalyst (sensitizer; e.g., something similar to chlorophyll) is embedded, possibly in connection with reaction partners, in such a way that one of the reaction products appears in the compartment on one side of the membrane, the other, complementary, product in the opposite compartment. In the given case, the two complementary products will be an oxidizing and a reducing primary species. Finally, these species will give O_2 and H_2, respectively.

No such vectorial reaction system has so far been constructed by man. Indeed the tasks has not been recognized until recently. However, theoretically the construction of such system, is possible, as pointed out. It should not be beyond the power of modern physical chemistry, embracing thermodynamics, kinetics, photochemistry, electrochemistry and solid state chemistry, to build up such a system in a planned way, and to make it technically useful.

It has been computed (30) that with 250 watts/m^2, infrared included, and an energy yield of 10%, an area of 40 km^2 would be sufficient to provide 1 million people with energy at the rate of 1 kW. Therefore an area of 640,000 km^2 could supply all mankind with energy at the rate of 4 kW, roughly corresponding to energy consumption in Europe. These areas are to be compared with that of the Sahara, 10 million km^2. The need for the water, to be obtained from the seas, would be modest, much less than in irrigation; the plants use only 1 part of water in 1000 for photolysis, while 999 parts are lost in transpiration. It was also estimated (30) that at crude oil prices existing in 1978 and capital service of 10%/year photolytic hydrogen would be competitive if 1 m^2 of membrane, with associated equipment, could be provided at 20 dollars. At the prices in mid-1979 (185 dollars/ton crude oil) the figure would be 31 dollars already. The energy obtained in the hot deserts could be exported to the populated countries as electric current, or, through pipe lines, as hydrogen, methanol or hydrocarbon.

cc) Photosynthesis by plants

It is most encouraging to know that in Nature vectorial reaction systems have existed for 4 gigayears or so. Every single cell living now, whether photosynthetic or not, is equipped with membranes capable of vectorial reactions. Probably the utilization of the membrane principle for photosynthesis was invented by living organisms long after nonphotosynthetic organism (nonphotosynthetic bacteria) had used it in other ways, namely, for so called "active transport".* The most primitive plants, the blue-green algae, still common today, learned photosynthesis on the basis of vectorial membranes about 3 gigayears ago (1).

True, plants do not evolve free hydrogen gas. This would not make sense as the gas would be lost. Instead, the plants use the reducing equivalents obtained in the (primary) light reaction to make a reductant that is equally strong as hydrogen gas, but does not escape. Thus thermodynamically the achievement of the plant is as good as if it had made H_2 gas. The reductant consists of a well-defined protein, ferredoxin, Fd, in its reduced form.

* Even single, dissolved, molecules of enzymes may achieve vectorial reactions. Imagine that catalysis takes place in a hollow space within the enzyme molecule. In the simplest conceptual case, the reaction may consist of an isomerization, i.e. a conversion of A into B, and vice versa. Further assume that the hollow space has openings of different shapes to two different sides of the enzyme molecule so that A can pass only one of these windows, and B the other window. In this case, the reaction into the two opposite directions is necessarily coupled to emision into the two different compartments. In dissolved enzyme molecules, the overall effect is not noticed, as the compartments are not separate, but communicate. The great step was taken when the enzymes were included into membranes that really did separate the two compartments. Then we can speak of "macrovectoriality" rather than "microvectoriality".

Subsequently this reduced ferredoxin is used to convert carbon dioxide to biomass in reactions explained by *D.Arnon, M.Calvin* and others. No light is needed for this series of steps. Schematically, we can write in extreme abbreviation:

$$H_2O + Fd\,(ox) \xrightarrow{\text{light}} Fd\,(red) + O_2$$
$$Fd\,(red) + CO_2 \longrightarrow Fd\,(ox) + (CH_2O);$$

(CH_2O), the hypothetical building unit of a molecule of carbohydrate, indicates biomass. The brackets show that we are not speaking of the chemical substance CH_2O, formaldehyde. This does not occur in plants or, for that matter, in any living organism.

Of course, plants did not appear ready-made in Nature. They were preceded by simpler organisms, the photosynthetic bacteria, some of which still exist (1). In contrast to the plants, these bacteria are not yet capable of water-splitting. The idea that the primary reaction in plant photosynthesis consists in the photolysis of water is owed to the genius from the Netherlands, *C.B. van Niel.*

The achievements of the plants are just staggering. In optimum conditions in the laboratory, they operate with an energy efficiency of 30 %, i.e. in the combustion of the biomass about one third of the light energy originally put in is recovered. The plants use light quanta of all energies, i.e. colours, almost equally well, from violet to red. In agreement with *Einstein's* law, the products of photosynthesis are independent of the dilution, i.e. the intensity, of the light. In a wide range of intensities, efficiency also does not depend on dilution. Last not least, biomass is ideal for storage.

cd) Production of biomass

Quantitatively, the achievements of the plants are also impressive. About 100 milliard tons of carbon are extracted from (and returned to) the atmosphere per year, still about twenty times more than is injected into the atmosphere by industry now. Most of the biomass is produced, it now appears, on land rather than in the seas. As long as the photolytic production of hydrogen in artificial systems is not yet a reality, the solar-chemical option for the production of technical energy must be based on the utilization of biomass (5,31,32,33,34,35).

We should not return to the age-old methods of direct combustion of wood, etc., which are still in large-scale use in many parts of the world, but which are cumbersome and wasteful. Rather, convenient solid, liquid and gaseous fuels are to be produced by rational, scientific, processes. The methods for the photosynthetic production, the mechanical disintegration, the chemical conversion and the efficient combustion of biomass still require R & D on a broad front.

But is there enough biomass in the world? Should not all available land be reserved for conventional agriculture and silviculture? The present author confesses that at one time he, too, considered this objection against "energy farming" as valid. However, the figures show that at present only a tiny part of the photosynthate in the world is utilized by man at all-about 1.5 % for food and feedstuff, and 2 % for fibres, mostly timber, Therefore a great deal of plant matter will remain available for fuel even with strong increases in the production of food, fibres, etc. Moreover, the production of photosynthate is bound to be raised through the means in our hands (32,36,37): plant breeding, fertilization, improvements in farming methods, reduction of waste, reform of social structures. In every one of these fields enormous progress may still be expected. Just for orientation: some 5% of the present photosynthate could cover all present energy needs of mankind.

The part of the solar energy at ground level used for photosynthesis is shown in Table 4. The data refer to visible light only, about one half of the total energy flux. Infrared light, practically the whole of the rest, cannot be used by plants, though photosynthetic bacteria are able to do so. Again the figures are necessarily quite approximate.

Table 4. Energy in Biomass as Percentages of the Energy of the Incident Visible Light (Whole Plants)

World overall, annual yield	0.3
Natural ecosystem, temperate zone, annual yield	0.5
Wheat, Europe, annual yield	2
Maize, USA, annual yield	4
Sugar cane, short-time yield	6
Theoretical maximum, red light	30

ce) Practical methods in energy farming

Chemical conversion of biomass may involve fermentation, pyrolysis or reactions with steam (re-forming). In alcoholic fermentation ethanol is produced aerobically, in methane fermentation "biogas" is obtained anaerobically. Products of pyrolysis ("dry distillation") include methanol, a fuel, acetone, a valuable solvent, and charcoal. The essence of reforming is the conversion, at high temperature, of biomass into hydrogen and carbon dioxide, with subsequent elimination of the latter:

$$(CH_2O) + H_2O \longrightarrow CO_2 + 2H_2.$$

The hydrogen would be available for the hydrogen economy, mentioned before. In part, it could go to fuel cells.

For the time being, the methods for fermentation are most advanced (35). Biogas is made all over the world from agricultural wastes in thousands of small-scale units. The process is especially useful in connection with large animal farms. A problem consists in the utilization in summer of the part of the gas that is needed for heating in winter; on the whole, biogas must be consumed locally. In any case, development work is required to optimize the process, which at the moment is largely a matter of empirical skill.

In contrast to biogas, ethanol can be used nation-wide at least. In Brazil, large amounts of ethanol for use in combustion engines are obtained from sugar cane (31, 32), and it is the intention in that country to expand this technology greatly. Cassava is another plant considered as a source of ethanol (32). In countries with temperate or even cool climates, rapidly growing poplars are in the foreground. In wood, most of the fermentable biomass is present as cellulose. This is less easily converted into ethanol than the sucrose in sugar cane or the starch in cassava. So additional R & D is needed.

However, care must be taken not to upset the ecological, hydrological and climatological conditions in the countries. The consequences of large-scale changes in the plant cover and in the growth rhythms must be studied and discussed in good time. For instance, it may be doubted whether sufficient care is taken in Brazil, where apparently the cultivation of sugar cane and also of other plants is pushed ruthlessly without a satisfactory analysis of the long-term consequences. In particular, the ecosystem of the Amazonas area appears to be in acute danger (38).

These objections may not apply to the Swedish approach (11, 12). The "Secretariat for Future Studies", State-subsidized, has proposed that in 2015, with a national energy consumption 37% higher than now, 62% of the total requirements could be covered by biomass on the basis of existing forestry practices. A production of 10 tons of coal equivalent (7×10^7 kcal) per hectare per year is forecast. The biomass would be used partly to make liquid fuel, and partly to power fuel cells. By the way, also the rest of the energy requirements are to be covered at home: additional electricity through water power, wind power and solar cells, and low-temperature heat from sunlight. For the USA, it has been argued that timber from existing forests would be the best biomass for fuel (39; see also (32)).

Scientifically, the cultivation of photosynthetic single cells, notably algae (32, 35), is of great interest. Yield per unit area and unit time is very high, and little land is taken up. Various combinations with nonphotosynthetic microorganisms grown on town effluents, etc., are possible. The products can in principle be used for feedstuff or even for food, provided toxic contents of heavy metals are avoided. Alternatively, fuels can be made from algal biomass. It remains to be seen how after due R & D the economics will compare with those of farming and forestry.

In energy farming it is obligate that the amount of fossil fuel that goes into the production of biomass (for fertilizer manufacture, transport, etc.) does not approach or even exceed the biomass in energy content. *Pimentel* et al. have, in a famous study (40), shown that in USA maize (only the grain reckoned) now has an energy content only 2.8 times that of the "absorbed" fuel. Naturally, this index figure is even less favourable (lower) with animal products or generally with highly processed food. On the other hand, it is as high as 37 in US forestry (39). A list of values for many British products has been given (32).

It is a fortunate feature of biomass utilization that no immediate dramatic decisions need be taken, in contrast, e.g. to nuclear technology. Biomass in the form of waste, practically free of charge, is available already now and everywhere: straw, corn cobs, sawdust, wood bark, small wood and also organic material in effluents from towns and animal farms. By order of magnitude, the energy content of this biomass amounts to about one tenth of the total national energy needs in many developed countries; referred to home production of fuel, the fraction may be much higher still. Thus the processes for biomass utilization can in good time be studied and developed on the basis of these materials, which are otherwise useless and must even be disposed of at considerable expense.

4. OBSTACLES TO SOLAR ENERGY

It is seen that in many ways R & D is still needed before solar energy can make a major contribution. Except in respect to the solar cells, much of the needed fundamental knowledge has existed for many decades. None of the further fundamental research needed is expensive. Compared, for instance, to high energy nuclear and particle research it costs practically nothing. So why was applied solar R & D delayed, or not undertaken at all?

One thinks back to the hundreds of thousands of unemployed coal miners before the Second War and to the hunger marchers who demanded reopening of pits. Who at that time foresaw an energy shortage? Moreover, after the War we had the oil glut which seduced mankind to waste energy in the most atrocious way. Finally, there was the promise of nuclear energy, into which enormous sums of money were invested - often on the basis of military and prestige considerations rather than of a perceived need for energy. After all, the materials, the instruments and the skilled manpower are near-identical for military and for peaceful nuclear fission. To a large extent this also applies to nuclear fusion.

The figures in national budgets are illustrative. Thus in 1973, before the so called energy crisis, the US federal budget allotted to solar energy 4, but to nuclear energy 396 million dollars. Even after the shock in 1973 it was still forecast (41) that in the five-years period 1975 - 1979 only 80 million were to be spent on R & D in solar energy, 95 million in conservation, but 3670 million in nuclear energy, much of it for the fast breeder. For the 1980 budget, the US President has still proposed (from federal funds!) 504 million for the developmemt of the liquid metal fast breeder and 86 million for that of other nuclear power reactors(42), apparently in spite of the stop to the early deployment of breeder technology. The annual US expenditure for fusion has been at the 500 million dollar level for many years, and support for fusion is heavy also in the Common Market Countries (43), in the USSR and in Japan.

Fortunately, the share of solar energy has risen rapidly in recent years, and it accounted for 400 million in the 1978 US budget. This does not mean that all is well now, however. Critics feel that the accents within the solar energy programme are often misplaced (44). Innovative research rather than the construction of big, and economically unpromising, power stations is needed (13). Thus one quarter of the whole federal solar budget of the USA is spent on the power tower. This is in the hands of four large aerospace contractors, including Boeing and Douglas. The large budget is not consistent with the prospects of economic success (45). Similarly the electricity production by the OTEC principle is most uncertain economically (45). As one critic said, solar technology is created in the image of nuclear power (9).

A striking example of gigantism is SPS (Solar Power Satellite), promoted by *P.E.Glaser* (46). The "reference SPS", power 5 gigawatts, takes the form of a rectangular array of photovoltaic cells, about 5 km times 10 km (!) that floats in space in a stationary orbit. It radiates its output to Earth by means of microwaves from an antenna formed by a flat circular structure about 1 km in diameter. Needed are a facility to handle about 100,000 tons per year of construction material and an orbital construction force of 550 men.

What really should be most actively supported, in addition to production of low-temperature heat, are technologies that take account of the dilute and intermittent nature of sunlight, including solar cells. Also the effort in respect to biomass should be greatly increased (45). In 1977, out of a total of 290 only 10 million dollars were devoted to biomass. Let us hope that the problem has now been understood. For 1979 already 27, and for 1981 no less than 119 million dollars have been earmarked for biomass R & D (13).

Systems analysis shows that the difficulty of the storage problem has been much overrated (47). We have mentioned the promising developing work of the Swedes in respect to storage of low-temperature heat. In connection with the important object of decentralized, small-scale, power either through the farm concept or through arrays of solar cells, storage batteries are not excessively expensive. Moreover, much more economical batteries, e.g. based on the solar energy are meant to give orders of magnitude only. Whatever the precise values, countries may be ready for considerable sacrifices in land to solve that main problem, supply of energy. These considerations apply independently of the solar option chosen, provided an energy yield of 10% is obtained.

Moreover, we should not aim at full, parochial, self-sufficiency, and some international trade in energy should remain. Energy is one of the main commodities that hot arid countries can export, so that they can make a living. They have more space and more sunshine. On the other hand, investment and technology must for a long time continue to come from the temperate zone. It is essential that the problems arising will be solved in a spirit of collaboration, and not of domination. In this way world peace will be served.

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