Chapter 4

Solar Energy and Its Utilization

SOLAR ENERGY SUPPLY ON EARTH

Let us now look closer at the role of solar energy in the energy household of life. At the outer boundaries of the earth's atmosphere, about 2.0 cal of energy (the amount of energy sufficient to heat 2 g. of water by 1°C) strikes, every minute, one square centimeter of the earth's cross-section. This is the so-called "solar constant"; its value means that about 1.25×10^{24} cal (1.25×10^{21} Kcal) of solar energy are received annually by the earth as a whole. Only about 40 percent of this energy, or 5×10^{20} Kcal, reaches the surface of the earth. The rest is either absorbed by the atmosphere (by oxygen, ozone, carbon dioxide, water vapor, and dust) or scattered into space. Together with radiation reflected by the surface of the earth—particularly where it is not covered by vegetation—this scattered light makes the earth shine like a star for an extraterrestrial observer, in the same way a dust particle shines in a beam of sunlight, or the moon and the cold planets shine at night for a terrestrial observer.

Despite these losses, if an economic method could be found to catch, store, and utilize the sunlight falling on our roof, it could easily cover all our domestic energy needs, while sunlight falling on large open areas could easily run all the wheels of human industry. Many attempts have been made to concentrate the energy of sunlight, for example, by means of giant concave mirrors, in order to utilize it for industrial purposes; but only minor economic successes have been achieved so far.

Concentration is needed if light is to be first converted to heat, because, according to the second law of thermodynamics, free energy can be extracted from heat only to the extent to which a temperature *difference* can be maintained; the greater this difference, the more work can be derived from it.

No such restriction applies to direct conversion of light energy into forms of energy other than heat, for example, into *electricity*. But a cheap and efficient method of such conversion has not yet been invented. Expensive devices of this kind, with a relatively high conversion yield, (of the order of 10%) are the so-called "solar batteries." They have been used as energy sources in satellites and spaceships. But one cannot economically cover large roof surfaces or land areas with highly purified silicon or other similarly expensive materials! And, so far at least, only such materials have been found suitable for the construction of solar batteries.

It is also theoretically possible to convert light energy directly into *chemical* energy, but as yet no effective and cheap way of doing this has been found. The problem is not only to find a cheap photochemical system that would store a substantial proportion of light absorbed in it; in addition, storage would have to be in a convenient form, permitting easy removal of the stored energy as needed. The answer could be a light-produced explosive mixture, a light-produced fuel, or a light-charged storage battery. None of these devices has been yet developed successfully.

To satisfy its energy needs—food, fuel, and industrial power—mankind now depends almost entirely on plants. These organisms have solved the problem of converting light energy into chemical energy with a rather low average yield, but on a vast scale. Reserves of this energy, stored in past geological areas, are available to man as fossil fuels (coal, oil, peat). Amounts currently accumulated by growing plants provide all human food (either directly, as vegetables, or indirectly, as meat or milk or animals fed on plants); a small fraction of fuel is provided in the same way, as wood or dung.

The utilization of energy stored by plants occurs by reversing photosynthesis—rapidly, in furnaces and explosion motors, or slowly, in respiring cells of plants and animals. In technologically advanced civilization, industry consumes hundreds of times more energy than human beings use up as domestic fuel. The maintenance and growth of this civilization now depends largely on the earth's accumulated capital of chemical energy (that is, on its fossil fuel reserves) and only to a very small degree on current solar energy supply, stored by plants. Mankind uses annually about 10^{13} kW hours of energy from the earth's current income, and ten times more, about 10^{14} kW hours, from the earth's accumulated capital.

The plants store less than one percent of the total solar energy reaching the surface of the earth. Man could easily live from this energy *income* of the earth, if he were able to improve significantly on the plants' ways to store it. One possible approach is breeding more efficient plants; another is growing existing plants in a way that would increase their natural rate of energy storage; the third (mentioned before) is developing nonliving systems for solar energy storage, as effective—and cheaper!—than the present-day solar batteries.

Not so long ago the need for mankind to learn how to live within its income, as far as energy consumption is concerned, seemed truly crucial. This was so because fossil fuels were then the only known significant terrestrial energy reserves, and these were being used up at an alarming and ever-increasing rate. It seemed that a great crisis of industrial civilization, if not a threat to man's very survival, was only a few centuries away. The crisis has been postponed for several centuries by the discovery of nuclear *fission*. Its energy, too, is derived from fossil fuels of a kind—uranium and thorium ores. The supplies of these fuels is also limited; but they promise to last ten or twenty times longer than the supplies of coal and oil. Finally, if *thermonuclear* energy production, through fusion of heavy hydrogen to helium, proves technically and economically feasible—as we have reason to hope it will—man's fuel reserves will become practically inexhaustible, because heavy water, D_2O, forms about 0.015% of the ocean. Nevertheless, it is reassuring to know that fundamentally, mankind could live on earth without recourse to fossil fuels of any kind, nuclear or chemical, by utilizing the flow of solar radiation. Therefore, the study of methods for effective and economic conversion of solar energy into chemical or electrical energy should not be abandoned, despite the more glamorous prospects of nuclear fission and fusion.

It has been suggested, particularly by *Farrington Daniels,*[1] America's most persistent proponent of solar energy utilization, that solar and nuclear energy could complement each other. Nuclear energy stations must be large to be economical—the larger the better!—while solar energy may be most economical where cheap, small local units, such as solar heaters, solar cookers, or solar pumps, are needed. (The use of solar power in spaceships is in a different category because cost is no consideration there.)

In any case, it seems an intellectually intolerable state of affairs! Plants, from great trees to microscopic algae, are busily engaged all around us in converting light energy into chemical energy, while man, with all his knowledge of chemistry and physics, cannot imitate them. Not only are we unable to imitate photosynthesis *as a whole* (that means, both synthesis of organic material *and* storage of energy), but we have not yet found any alternative method to convert economically the energy of solar radiation into useful chemical or electrical energy.

Nature offers man, in addition to nuclear energy, some other energy sources, not derived from photosynthesis, present or past. The most important one, in the present state of civilization, is the energy of *falling water;* but it now accounts for only about 10^{12} kW hours annually, or about one percent of mankind's total energy consumption, and the possibility of its expansion is limited. In Europe and North America, more than one half of available water power already has been harnessed. Much more untapped water power remains in Asia. Russians are now busy harnessing the big rivers flowing northward into the Arctic Ocean, the Chinese struggle with the giant but unruly rivers running east into the Yellow Sea, and India has begun the construction of hydroelectric power plants on rivers flowing into the Indian Ocean. Large, unused sources of water power remain only in South America and, above all, in Africa, where the Aswan Dam on the Nile and the Volta Dam in Ghana promise to open new regions for industrialization. However, the total water power available for development on earth is limited, and while it may be important for industrial development of certain areas, it would not begin to solve the industrial energy problems of mankind as a whole.

It is worth noting that the energy of falling water also is derived

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[1] See Farrington Daniels, *Direct Use of Solar Energy,* Yale University Press, 1964.

from solar radiation. Sun heat evaporates water from the seas and thus causes rain. Rivers, fed on rain water, flow back into the sea and provide water power. The same is true of a large part of wind energy—the sun heats the atmosphere nonuniformly and thus causes winds. Use of wind energy for power is very old, but remains restricted—as all familiar with windmills in Europe and wind generators on American farms are aware.

Tidal energy, nuclear energy, volcanic heat, and wind energy associated with the rotation of the earth (rather than with its heating by the sun) are the only sources of energy on earth *not* derived from sunlight. Enormous amounts of *wind energy* go to waste, because of the difficulty of harnessing it for practical purposes. *Tidal energy* is being used, at present, only in one installation located near St. Malo in France. The use of *nuclear energy* is growing rapidly; it already accounts for about 40% of the current electric energy supply in England. About one half of newly installed electric generating power in America was based, in 1966, on nuclear fuel. *Volcanic* heat is as yet put to industrial use only in a few localities on earth, for example, in Italy.

GREEN PLANTS AS CONVERTERS OF SOLAR ENERGY

Vegetation covers all continents except the ice-coated Antartic and the deserts of Africa, Asia, and Australia. In the tropics and subtropics, vegetation utilizes sunlight all year round. In the higher latitudes, the activity of plants is reduced in winter. With the exception of the icy Arctic waters and other unproductive areas, the upper layer of water in the oceans also abounds in plants, predominantly free-swimming microscopic algae. Geochemists call the layer of organisms covering the earth the "biosphere," as if it were a thin spherical shell located between the lithosphere (earth's crust) and the hydrosphere (the world ocean) on the one side, and the gaseous atmosphere on the other. The biosphere is, however, not continuous. On land, it is interrupted by vegetation-free desert areas; in the ocean, it is not a separate layer, but is stirred up with the upper part of the hydrosphere, extending to a depth of several hundred feet under the surface—as far as light can penetrate into water. Dead organisms, plants or animals, sink to the bottom of the sea, and bacteria and some other deep-water organisms live in lightless deeps by feeding on their bodies. Despite these limitations, the term biosphere is graphic and useful.

The total amount of solar energy stored annually in the biosphere is given by the product: $A \times B \times C$ Kcal, where A is the solar energy flux hitting the earth's surface, B the percentage of this flux absorbed by plants, and C the percentage of absorbed light converted to chemical energy, with $A = 5 \times 10^{20}$ Kcal/year, $B =$ about 0.3,[2] and C about 0.01, the total is 1.5×10^{18} Kcal annually. However, the use of the same factors for plants on land and in the ocean is very uncertain.[3] If we make the calculation for fertile land areas only (that is, for about 20% of the earth's surface), we obtain a figure of 3×10^{17} Kcal stored annually, corresponding to 3×10^{10} tons of synthesized organic carbon. This value is somewhat larger than that given in Table 2.1, based on land crop estimates (about 2×10^{10} tons, after correction for respiration) but it agrees with it in the order of magnitude, which is as good as could be expected.

The *maximum* efficiency of energy conversion of which plants are capable under the most favorable conditions is much higher than the above-mentioned *average* efficiency. The *minimum number of light quanta* (atoms of light, also called photons) needed to reduce one molecule of carbon dioxide and liberate one molecule of oxygen, has been much studied because of the importance of this constant for the understanding of mechanism of photosynthesis. It will be discussed in Chapter 11. The most likely figure at present is eight quanta per molecule of liberated oxygen. Eight quanta of red light carry about 350 Kcal/einstein (one einstein of quanta being numerically equal to one mole—that is, 6.0×10^{23} atoms). The maximum conversion efficiency is thus $^{120}/_{350} = 0.34$. A conversion yield of one percent, suggested above as average under natural conditions, corresponds to as many as 280 quanta per

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[2] Over 50% of the solar light energy striking the earth is in the infrared spectral region, not absorbed by photosynthetic pigments. Of the remaining 50%, only about 60% is likely to be absorbed by the plants, rather than reflected from the surface of the ocean, sands, rocks, or the plants themselves.

[3] See Chapter 2 for considerably lower estimates of the average energy utilization in the ocean.

oxygen molecule of which all but eight are wasted as far as photosynthesis is concerned. (They do, however, contribute to another plant function—transpiration.)

Of the total 2–3 $\times 10^{17}$ Kcal stored by land plants each year, man utilizes as food about one percent, or 2–3 $\times 10^{15}$ Kcal annually (about 2×10^3 per day for each of 3×10^9 people on earth).

Storage of light energy as chemical energy through photosynthesis can be envisaged as a stage interpolated in the conversion into heat of the solar energy striking the earth. A steady state is established, in which a certain amount of light energy, received by the earth, is channeled off to run the "mills of life," before it is degraded into heat. Sometimes, as in the formation of coal and oil, this temporary storage of sunlight is extended over millions of years, by spatial separation of synthesized organic matter from oxygen under the cover of minerals, or under a salt dome. Sooner or later, most of the energy stored in fossil organic matter (plus atmospheric oxygen) will be dissipated by men who dig coal from under the protective layer of rock and burn it in furnaces, or pump oil from under the salt domes and use it in internal combustion engines.

From the point of view of energy transformation, the position of life in nature is similar to that of a mill built on a spillway, parallel to a waterfall (see Figs. 3.2 and 3.3). It interrupts the spontaneous process of energy degradation, represented by the conversion of light to heat or by water freely streaming downward, and diverts a part of the free energy of this degradation to useful purposes. Plants are chemical factories in which organic products of high chemical energy content are synthesized. These products are, in principle, unstable in the presence of oxygen. They perform their transformations, which are the essence of life, like acrobats on a tightrope, high above ground, surrounded by an ocean of air that continuously threatens them with annihilation. Living organisms manage to regulate the rate of this annihilation process, thus providing measured amounts of energy needed for their activities. When they die, the annihilation is completed by scavenger organisms utilizing the residual chemical energy of dead bodies for their own living processes.

Light energy is stored in photosynthesis as free chemical energy. The latter is then used by organisms for their various life activities. The *energy conversion* cycle, represented by photosynthesis and respiration, is thus coupled with a giant *chemical cycle* in which carbon dioxide and water are converted into organic matter and oxygen, and the latter back into carbon dioxide and water (see Figs. 2.1–2.3, 3.2 and 3.3). Water is the "working fluid" that mediates the transformation of heat energy into mechanical energy in a steam engine; CO_2 and H_2O are "working fluids" that mediate the transformation of light energy into life energy in plants. Water and carbon dioxide are exceptionally stable chemical compounds. They represent the most stable form in which the three elements, carbon, hydrogen, and oxygen can exist together, the lowest possible energy level of the working fluid, like cold water in the condenser of a steam engine or water in a reservoir downstream from a hydro-electric station. All useful free energy has been extracted from the system in this exhausted state. The correlated high-energy state is that of organic matter and free oxygen—similar to that of water behind the upstream barrage, or of hot steam in the boiler (Fig. 3.3).

The carbohydrates synthesized by photosynthesis are only in part utilized directly for the reverse, energy-supply process of respiration. Another part serves as raw material for a variety of chemical transformations, of which polymerization and amination (that is, introduction of nitrogen into the organic molecule) are the most fundamental ones. Some products of these transformations (cellulose, bone, cartilage, etc.,) become permanent structural parts of the organisms. Other products (fat, starch, etc.) serve as storage material, and still others (proteins, nucleic acids, vitamins) play an important role as catalysts in metabolism. Ultimately, all of them are degraded back into carbon dioxide and water, either in the normal course of life, or in decay after death.