Solar Energy

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FROM THE DAWN OF HISTORY man has realized the importance of the sun, but only in the present scientific age has he begun to appreciate the vastness of this source of energy and the extraordinarily clever mechanisms by which nature makes efficient use of it. In these times of profligate spending of the world's natural resources (*12*) and uncontrolled increase in population (*12, 18*) it is our task on this 100th anniversary of the founding of the American Association for the Advancement of Science to try to see what lies ahead. Science has pulled us out of many difficulties in the past—and has given us the means for getting ourselves into worse ones. When we have used up our coal and oil, exploited our available land with intensive farming, and trebled our population, can we then call on the sun to give us still more means to satisfy our ever increasing demands for food, fuel, and power? *The answer is yes.* But there is a long challenging road of research and development which must be followed first—and we must not get the idea that we are about to step into a new era of physical and economic abundance. We can't eat sunshine, we can't carry it where we want to use it, and, because it cannot easily be used to produce high temperatures, we find it is difficult to apply directly in our heat engines.

Amount of Solar Energy

The earth intercepts a prodigious amount of radiant heat from the sun (*13*)—about 5×10^{20} large calories or kilocalories per year, arriving at the surface of the earth. Five followed by 20 zeros is too large a figure to register with most of us, but suppose one considers the amount of energy in terms of an acre. An acre is roughly a square of land 200 feet on a side, a little less than the length of half a city block, with an area of about 40,000 square feet. In most parts of the United States the solar energy averages more than one kilocalorie per square foot per minute (*6*), or 500 kilocalories per day. Since each one of the 40,000 square feet in an acre receives 500 kilocalories each day, the whole acre receives 20,000,000 kilocalories per day. Let us see what these figures mean in terms of food, fuel, and power. In the continental United States there are now nearly 144,000,000 people and nearly 2,000,000,000 acres of land (*21*), giving an average of about 14 acres per person, and a theoretical average of 280,000,000 kilocalories of sunlight per day per person.

Each person uses about 3,000 kilocalories to maintain himself with food, and vastly more for heat and power. In 1946, 583,000,000 tons of coal (*22*) were used for, heat, light and power by 140 million people in 365 days—an average of 20 pounds person per day or 75,000 kilocalories; 1,700,000,000 barrels of oil were used for heat and power including automobiles —an average of 50,000 kilocalories per person per day; nearly 4,000,000,000,000 cubic feet of natural gas were used, an amount equivalent to 21,000 kilocalories per person per day. On the average then, each person had 3,000 kilocalories from food and 146,000 from coal, iron, and gas—a total of nearly 150,000 kilocalories per day. When this total is compared to his theoretical average of 280,000,000 kilocalories from the sun, we see that the sun supplies to the United States nearly 2,000 times as much heat energy as is now used. It must be emphasized that most of the heat energy now used comes not from the daily supply of solar energy but from the solar energy stored up in bygone ages.

Utilization of Solar Energy

Of the sun's radiation which hits the earth's atmosphere a considerable portion is reflected and scattered, so that about 1 kilocalorie per minute on the average, in the Temperate Zone, reaches a square foot of land or water. Some of this is used in the evaporating of water which, however, releases this heat again when the water vapor condenses as rain or snow. Most of the visible sunlight, constituting about half of the total radiation reaching the earth, can be used for producing carbohydrates and other organic material if it strikes growing plants on land or in the sea, and the remainder is available for raising the temperature. The tendency for the earth's temperature to rise, due to solar radiation and by decay of radioactive elements in the earth, is nicely counterbalanced by the cooling caused by infrared radiation from the earth corresponding to the earth's temperature (*2*).

How can we convert this 20,000,000 kilocalories per acre per day into useful power? If it could be used to operate a modern steam engine or hot gas engine with a normal efficiency of 25 per cent, we could obtain electrical power equivalent to 240 kilowatts per acre. But this plan is not now practical because the sun's radiation falling on the earth's surface does not create high temperatures unless it is concentrated or special precautions are taken to reduce heat losses.

"Solar Energy" was one of the addresses delivered at the Symposium on Sources of Energy, held in Washington, D. C., on September 15, during the Centennial Celebration of the AAAS.

Just as we must have a difference in level, that is, a waterfall, for a mass of water to produce hydroelectric power, so we must have a difference in temperature for heat to do work. The maximum efficiency obtainable is completely set by the difference in temperature, divided by the higher temperature. The possibilities and limitations of utilizing solar energy for engines and for house heating have been considered by Professor Hottell (*8*) of MIT. He estimates that an acre of Arizona sunshine might produce 37 kilowatts or 50 horse power and New York sunshine might produce 23 kilowatts or 30 horse power. He concludes that we do not yet have enough facts to determine the economic practicality of solar engines. It may be noted in passing that it usually takes more than one acre of sunshine on farm land to support one horse and that an average farm horse does not work more than 1,000 hours out of 8,766 hours in one year.

Even with expensive lenses or reflecting mirrors spread over a large area, it is not easy, even on cloudless days, to raise the temperature high enough to give very efficient conversion of heat into work; and when the sun is obscured with clouds, a focusing system is inoperative.

Some attempts have been made to operate vapor engines with low-boiling liquids or with water under reduced pressures. These engines are rendered somewhat more practical if they can be located near a large body of cold water to cool the condensers to a low temperature, but the small temperature difference and the low thermodynamic efficiency is a serious handicap.

Windmills are operated, of course, by differences in air pressure caused by solar energy—but, although they are very useful in certain areas, they are sporadic in operation and do not seem destined to play an important role in meeting the demand for large amounts of power.

Let us consider another approach for the direct conversion of heat into work. Thermocouples made by joining two wires of unlike metals will generate electricity when one junction is hotter than the other. We can produce electricity by placing one junction in the sunlight and one in the shade, but the voltages obtainable are of the order of a few thousandths of a volt per junction and, if we use a large number of junctions in series, we automatically increase the resistance of our wires to very large values. On a small scale, intense radiation from the sun can be converted into electricity with an efficiency of a few per cent with expensive equipment. The best commercially available thermocouple material can convert 0.8 per cent of the sunlight absorbed, under favorable conditions, into electricity. Special alloys in the laboratory give promise of a still higher conversion (*16*).

We have photochemical cells which generate electricity when one of the electrodes is exposed to the light and the other is kept in the dark. Again the voltages are very low and the resistances very high so that direct generation of thousands of kilowatts of electricity does not now appear to be practical. For house heating, high temperatures are not required and here seems to lie an opportunity for making more use of the sun. Hot water for houses is now being provided by solar radiation (*3*). Certainly all scientific principles should be followed in the use of absorbing and reflecting surfaces to obtain maximum heat from the sun in winter and minimum heat in the summer. Heat storage beds of cheap, quick, heat-exchanging materials should be more thoroughly explored as a means for equalizing temperature—storing the heat of the day to be blown through the house during cool nights and storing the cold of the night for air conditioning on hot days. An attractive approach lies in the storage of solar heat in chemical or physical changes. Miss Maria Telkes, of the Massachusetts Institute of Technology, is conducting practical research along these lines, and she has summarized the situation with reference to solar house heating (*17*). Lof (*9*) and others have studied the problem of house heating.

Although solar engines for power and mechanical devices for storing solar heat are not impossible, they do not now appear to be practical enough to be important on a large scale. We must look elsewhere for the conversion of sunlight into useful power and stored heat. Let's consider using the sunlight to bring about some cheap, efficient photochemical reaction to obtain a product which we can carry around with us and then release the stored energy when and where we please by a second chemical reaction. It would be a good idea to combine carbon dioxide and water to form carbohydrates and other organic materials, and then burn them in the oxygen of the air with the evolution of heat at high temperatures. This sounds like a good idea but there are two serious difficulties—neither carbon dioxide nor water absorb sunlight, and without absorption there can be no photochemical reaction. Even if we found a third substance which would absorb the sun's radiant energy and transfer it in some mysterious manner to the carbon dioxide and water, the energy in the units of radiation, called photons, amounts to only about 40 to 60 kilocalories per mole while the energy required to make carbohydrates from carbon dioxide and water is more than 112 kilocalories per mole. Nevertheless, nature solved this problem in a very beautiful manner with chlorophyll and started production of carbohydrates in growing plants soon after the earth cooled enough to permit the existence of organic material.

This process, in which carbon dioxide and water are transformed into carbohydrates by sunlight in the living plant, is called photosynthesis.

Nature did us another good turn by accumulating this carbohydrate material over millions of years, altering its chemical structure to give a greater percentage of combustible carbon, and storing it, so that we can have convenient fossil fuels packaged as solids, liquids, or gases—coal to be shoveled and shipped in chunks, petroleum to be pumped and carried in tanks, and natural gas to flow easily through pipes.

Again man was provided with a means for getting work done long before he had evolved far enough to invent heat engines. He could obtain mechanical power from the organic material, photosynthesized by the sun, by feeding it directly to men, horses, water buffalo, or other animals, and then persuading them to do his work for him. The conversion of chemical energy into useful work in this intricate animal process is not limited, as heat engines are limited, by the requirement of a large difference in temperature, but by other factors not yet fully understood.

TABLE 1

TYPICAL AGRICULTURAL UTILIZATION OF SUNLIGHT

Crop	Crop yield/acre/year
Corn (1946 average, U.S.)	33 bushels (0.9 ton)*
Wheat (1946 average, U.S.)	17 bushels (0.5 ton)*
Hay, tame (1946 average, U.S.)	1.5 tons
Hay, wild (1946 average, U.S.)	0.9 ton
Florida pine (total wood material)	3 tons
Wisconsin aspen (total wood material)	2 tons

* The organic material (cellulose) of leaves, stalks, etc. gives an additional .9 ton, approximately, for corn and 0.5 ton for wheat.

More recently man has tried to compete with nature in using atomic energy under controlled conditions, but the much publicized atomic energy cannot compare with the sun's energy. An atomic bomb with its equivalent of 20,000 tons of TNT has 20,000,000,000 kilocalories, which is no more than the heat of the sunlight which falls on 1½ square miles of land in a day.[1] The difference of course is that in an atomic bomb the energy is wrapped up in a small package and released instantaneously. Only a small fraction of the sun's energy can be utilized in any operation which involves high temperatures.

PRODUCTION OF FUEL AND FOOD

Of the nearly 2,000,000,000 acres of land in the United States (*13*) a little more than half is used for farming and about a third is forest, the rest being largely grazing land, desert, mountains, and city land. Much of our land, therefore, is now using the sun's radiation to grow vegetation of some kind—crops, forest, or grass—but the utilization of solar energy is often inefficient.

In Table 1 are shown average yields per acre for four crops in the United States for 1946 (*20*).

EFFICIENCY OF PHOTOSYNTHESIS

We have just seen what average yields are now obtained in the conversion of sunlight into plant material and have learned that two tons of wood material can be grown in a year on an acre of aspen in Wisconsin under good operating conditions of continuing forest growth. When this annual growth of wood material is burned, it will yield 8,500,000 kilocalories, whereas the sun's radiation falling on the acre is 7,300,000,000 kilocalories per year. This results in a return of a little less than 1/10 of 1 per cent of the sun's energy.

The case is somewhat better with corn on fertile soil. On some Iowa farms the yield of shelled hybrid corn is 100 bushels per acre and the weight of the cobs, leaves, stalks, and roots is about equal to that of the corn. If all this organic material is burned, about 20,000,000 kilocalories will be evolved, amounting to a conversion of 3/10ths of 1 per cent of the year's solar radiation. If one remembers that the growing season is less than a third of the year, it is evident that the corn actually converts about 1 per cent of the possible radiation into organic material. According to one experiment in which the light was measured and the corn and leaves and roots accurately weighed, a conversion of 1.6 per cent was obtained during the growing season (*11*), or about 0.5 per cent of the year's sunlight.

What are the factors which make for this low efficiency? As just explained, the growing season is short—only about a third of the year. The green chlorophyll of plants does a remarkable job of absorbing light all the way from ultraviolet light to red light at 6,800 A and utilizing it in photosynthesis, but even so it does not absorb more than half of the total range of the sun's radiation. Most of the other half lies in the heat rays or infrared radiation. Again, particularly in the first part of the growing season, the plants are small and much of the acre is not covered with leaves. The layers of leaves are not thick enough to absorb all the absorbable light. Obviously, it is only the light which is absorbed by the plant that can have a part in photosynthesizing new plant material.

In order to obtain the maximum production, all the conditions must be optimum. For example, if sunlight is to be the limiting factor in getting the maxi-

[1] One gram of TNT is equivalent to 1 kilocalorie; 20,000 tons of TNT = 2×10^4 tons $\times$ 2×10^3 lbs/ton $\times$ 453 grams/lb $\times$ 1 kilocalorie/gram = 1.8×10^{10} kilocalorie; 1½ sq mi = 960 acres; 960 acres $\times$ 20 $\times 10^6$ kilocalories/acre = 1.9×10^{10} kilocalories/1½ sq mi.

mum amount of plant growth, the other necessary major and minor chemical elements must all be present in adequate amounts. For, example, a given amount of sunlight will not give the maximum growth of plant material if the plants are too dry, or the weather too cool, or the ground too poor in soluble, essential minerals. Moreover, when the light intensity is increased, the efficiency of conversion is decreased.

The concentration of carbon dioxide in the air is only 0.04 of 1 per cent, and there is no simple way of increasing this concentration in open fields. All plant material gets its carbon from this 0.04 per cent in the air. This seems to be a small source of carbon for all the vegetation of the world, but in the air over each acre there is 19 tons of mobile carbon dioxide.[2]

What is the theoretical limit to which efficiency in photosynthesis can approach when all other factors involved are present in abundant quantities and sunlight becomes the limiting factor? Under optimum conditions, nearly 10 units of radiation, called photons, must be absorbed by chlorophyll in order to cause the combination of one molecule of carbon dioxide and one molecule of water to give as much carbohydrate as is equivalent to one atom of carbon. These are experimental values, obtained with green algae in water with ample carbon dioxide, perhaps 5 per cent, and plenty of chemical food material and low light intensity. As we shall see shortly, this ratio of 10 photons per molecule means that, with green light, under the most favorable conditions, only 20 per cent of the energy of the light can be stored as chemical energy.

Remembering the 1/3 factor for the growing season and the 1/2 factor for utilizable sunlight, even with the best environment of moisture, fertilizer, and temperature, we could expect to get only 1/6th of 20 per cent or 3 1/3 per cent conversion of sunlight in an agricultural crop in the United States. The 0.3 per cent conversion of the annual sunshine in a bumper corn crop is not bad in comparison with the theoretical maximum of 3.3 per cent.

This maximum ratio of about 10 photons of light absorbed per molecule in photosynthesis has been checked in different laboratories (*10*) in several different ways. The chemical change has been determined by micro-gas analysis, by electrical methods, by chemical titration for oxygen, by differential measurements in a Warburg manometer, and by optical and magnetic methods.

Perhaps the most significant and independent measurements have been made calorimetrically (*1*). A tiny glass cell is surrounded by thermocouples which measure the heat evolved when the light passes through the cell. The light absorbed by algae in the cell is measured at the back of the cell. Of the light which is absorbed by the algae growing under optimum conditions, about 80 per cent is converted directly into heat in the calorimeter, thus leaving only about 20 per cent which can possibly be stored as chemical energy in the carbohydrate and other plant material.

Mechanism of Photosynthesis

We are just beginning to understand something about the mechanism of photosynthesis. With all the millions of dollars invested in agricultural research, it is strange that so little has gone into the fundamental process of photosynthesis which underlies all of agriculture. Few studies on photosynthesis have been made by federal or state agricultural laboratories; and active programs of work in quantitative photosynthesis has been in progress at only about a dozen universities and institutions.[3] Three symposia on photosynthesis have been held—under the Chemistry Section of the American Association for the Advancement of Science.[4]

The fundamental reaction of all plant life involves the combination of carbon dioxide and water. When a carbohydrate like sugar or cellulose is burned the reaction is represented as follows:

carbohydrate + oxygen = carbon dioxide + water + 112 kilocalories

$$1/n(CH_2O)_n + O_2 = CO_2 + H_2O + 112 \text{ kilocalories}$$

If this reaction is reversed at least 112 kilocalories must be absorbed and, unless the processes are 100 per cent efficient in all their steps, the amount of energy required may be much more. The reaction occurring in the plant is written as follows:

[2] (0.0004 × 15 lbs/sq inch × 43,560 sq ft/acre × 144 sq inch/sq ft) ÷ 2,000 lbs/ton = 19 tons/acre.

[3] Including among others: University of California (isotopic tracers and mechanisms); Carnegie Institution of Washington at Stanford University (plant pigments and photochemical efficiency); University of Chicago (mechanisms, fluorescence, isotopic tracers, and photochemical efficiency); Harvard University (efficiency of forest growth); Hopkins Marine Station (enzyme reactions, photochemical efficiency, and various algae); University of Illinois (general photosynthesis and photochemical efficiency); Iowa State College (absorption of light by leaves); Kettering Foundation at Antioch College (chlorophyll and related plant pigments); University of Minnesota (chlorophyll and related pigments, photochemical electrical cells, isotopic tracers); Smithsonian Institution (influence of color and intensity of light on plant growth); University of Texas (protein production in algae); University of Wisconsin (photochemical efficiency and mechanisms); Massachusetts Institute of Technology (direct utilization of solar energy).

[4] Symposia, AAAS, Section C, Columbus, Ohio, 1939; Gibson Island, Maryland, 1941; Chicago, Illinois, 1947.

carbon dioxide + water + chlorophyll + > 112 kcal = carbohydrate + oxygen

$$CO_2 + H_2O + (\text{chlorophyll}) + > 112 \text{ kcal of sunlight} = 1/n(CH_2O)_n + O_2$$

Green light corresponds to 55 kilocalories per mole, and two photons must be brought together to provide this minimum of 112 kilocalories per mole. Red light of 40 kilocalories per mole requires nearly 3 photons per molecule to meet the *minimum* energy requirement of 112 kilocalories. In actual photosynthesis, we have found that about 10 photons are required for one molecule. Now this use by nature of several low-energy photons to do a high-energy job is unique. We haven't done it yet with inorganic materials, and only in the last few years are we beginning to understand how nature does it.

Several laboratory findings have contributed to this understanding. In the first place, earlier theories of photosynthesis were handicapped by the belief that photosynthesis is very efficient, about 60 per cent (*19*) instead of the 20 per cent now accepted. In the second place, important advances have been made recently in understanding enzyme chemistry and the utilization of energy in yeast, bacteria, and other biological systems.

Many miscellaneous facts are known concerning photosynthesis which are helpful in developing a satisfactory theory. Only a few can be mentioned here.

Green chlorophyll absorbs the light and acts as the intermediary for supplying the energy from the sun which is required in the complex series of reactions by means of which the carbon dioxide and water combine to give carbohydrate. Chlorophyll has intense absorption bands in the red and blue, but in thick layers it absorbs light throughout most all of the visible spectrum. The maximum efficiency of photosynthesis is nearly the same for red, blue, or green light. Respiration, which is the reverse of photosynthesis, goes on continuously in plants. The plants, like animals, consume oxygen and give off carbon dioxide. The addition of glucose and other soluble organic foods increases the rate of respiration of plants, but it does not affect the rate of photosynthesis.

The ratio of oxygen evolved to carbon dioxide absorbed is often about 1 to 1, but this can be true only for the production of cellulose and other carbohydrates. The ratio cannot be unity in those plants and algae which produce considerable amounts of proteins and fats. An exact determination of the oxygen-carbon dioxide ratio is helpful in giving information concerning the composition of the organic materials produced in photosynthesis.

The photo reactions pile up fresh organic material, which is used by the plant in a series of reactions which go on in the dark. Valuable information concerning the dark thermal reactions and the photo reactions has been obtained by exposing plants to intermittent light with dark periods ranging down to fractions of seconds (*6*). Again the dark and light reactions can be partially distinguished by changing the temperature because the dark reactions are accelerated by an increase in temperature whereas the photo reactions are nearly independent of temperature.

One of the newest and most promising attacks on the mechanism of photosynthesis lies in the use of isotopic tracers. When plants are grown in carbon dioxide which contains radioactive carbon, the first chemicals produced in photosynthesis are identifiable by means of their radioactivity. Active and significant work is now going on with radioactive carbon (*14*). Experiments with water containing the heavy isotope of oxygen revealed the significant fact that the oxygen released in photosynthesis comes from the water (*15*) and that the oxygen of the carbon dioxide remains in the plant materials.

With the help of these laboratory findings and many others, a satisfactory hypothesis is beginning to unfold. Following the primary photo reactions are many thermal reactions which are aided by enzymes. The over-all energy requirement of more than 112 kilocalories is too great to be met by one unit of light, one photon, and the reaction must be carried out in a series of steps, one photon being used for each step.

Apparently the carbon dioxide adds to an organic substance of low molecular weight and forms a carboxyl or acid group. This new substance is subsequently reduced by hydrogen made available through the photochemical dehydrogenation of water. Perhaps four steps are involved, each requiring a photon; and then four more reactions with four more photons are required to restore the hydrogen atoms to these intermediate compounds, ready to be used again. This gives a total of eight photons through a series of eight intermediate steps, which carry the hydrogen from the water to the carbon dioxide, thus releasing oxygen and forming the carbohydrate material, CH_2O. If this picture, proposed by James Franck, of the University of Chicago, is correct we have a plausible explanation for the experimental fact that about ten photons are required.

The Next Hundred Years

When it comes to predictions, the news reporters probably take delight in pushing the scientist out on a limb—just to see the splash. However, on this 100th anniversary there may be a legitimate demand for a little speculation.

The days of easy geographical quest for more food, fuel, and power are over, and our frontiers now lie in science and engineering. We can no longer afford to waste valuable fuel in fireplaces and stoves that send most of the heat up the chimney nor in low temperature engines that are thermodynamically inefficient. An *average* steam locomotive converts not much more than 5 per cent of the heat of the burning coal into useful work. In the future, it will be necessary to increase the efficiency of our utilization of sunlight, to conserve all our resources, and to control the birth rate of the world's population. We have seen that we are now using only a small fraction of the solar energy which is available and that, theoretically, we should be able to appropriate a much greater part of it. We have seen that present prospects are not bright for the conversion of solar energy into electrical power through heat engines, thermocouples, or photochemical cells, but revolutionary discoveries might well lead to more optimistic possibilities.

Our discussion has emphasized the situation in the United States because it was difficult to obtain statistical information regarding the utilization of sunlight over the whole world. We are emphasizing on this anniversary occasion, however, that science is worldwide. Let us add, then, that the area of the United States is but a small fraction of the earth's surface and that any improved conditions must be thought of in terms of world application. In the tropics there is a greater opportunity for utilizing solar energy because the energy is greater than the 1 kilocalorie per square foot per minute in the United States and the growing season is not confined to a third of a year. The soil and certain agricultural conditions are somewhat less favorable however. Also to be considered are the great areas covered by oceans where photosynthesis goes on in diatoms and other sea plants. Perhaps more organic material is being produced now in the sea than on the land.

It is possible now to grow plants without soil, using barren sand or tanks of water containing the necessary chemical elements. This science of hydroponics has been developed to a point where such operations are practical, even if not economically competitive except in special areas. Probably the utilization of sunlight can be made more efficient in this way and the operation can be applied where there is no soil suitable for ordinary farming.

Let's consider one step further. What chance is there that we can combine carbon dioxide and water to give organic material without the agency of a living plant? We can perhaps find some combination of colored dyes and enzymes which will do what nature now does with green plants? This has not been done yet, but there is no obvious theoretical reason why it cannot be done some time in the future. As a matter of fact, if someone had asked me to guess ten years ago which would come first, atomic energy or photosynthesis without the living plant, I would have guessed the latter. But now we have atomic energy —or at least we *can* have it. It resulted from the unexpected discovery of fission, an investment of five years of intensive coöperative research by many hundreds of scientists and engineers, and the expenditure of $2,000,000,000. The corresponding investment in photosynthesis has been negligible. A really large program of research on the greater utilization of solar energy might produce significant developments. Solar energy is our most promising resource in the long-range view.

There is no assurance that photosynthesis outside the living plant will be any better or cheaper than present photosynthesis in plants. Very likely agricultural research similar to that already carried out will provide our best means for increasing the efficiency of our utilization of solar energy where the soil is good.

Even if we could produce food without the growing plant, our present farms would not fear competition from the cheap land and bright sunshine of Arizona. Any type of artificial photosynthesis would probably require shallow tanks, possibly of concrete covered with glass, and the investment would be too great to consider in economic competition. Moreover, any possible development of this kind would come slowly enough to give ample time for economic and social readjustment. Scientists of the future should consider photosynthesizing organic or inorganic products of an energy content lower than cellulose and carbohydrates. It might be easier. Possibly they might tackle the problem of muscular action produced by chemical reactions involving photosynthetic material, thus attempting to follow the pattern of animal work. There are serious limitations in efficient conversions of food energy into animal work, but they are perhaps less well defined than the second law of thermodynamics, which limits the efficiency of heat engines.

Looking less far into the future, what important changes are apt to come? We shall have to find ways to increase the food and fuel supply of land areas which are not now suitable for growing standard food crops. The wheat and meat of the limited, rich, farming lands cannot be used indefinitely to feed the world. Trees and quick-growing bushes and grass can be grown on poorer soil, and it is now perfectly practical to eat wood products. In fact, thousands of tons of wood yeast were used for human food in Germany during the war. Sixty-five to 70 per cent of most woods can be converted into sugars by heating with dilute sulfuric acid to 120°–150° C under special conditions (*7*) developed at the U. S. Forest Products Laboratory. This material can then be used for growing yeast and producing alcohol which can be used for liquid fuel. The wood yeast is as rich in proteins as beef steak and can be used for food.

These cellulose yeasts are cheap, and they possess splendid nutritive value. With intensive research on improving the flavor, this source of protein should be of great help in solving a food shortage, particularly in the tropics, where the large-scale production of meat is difficult. Nitrogen compounds must be supplied to these growing yeasts in order to produce proteins. Possibly this fixed nitrogen can be supplied directly from the nitrogen of the air by a new process in which the air is heated to a high temperature. Present methods of utilizing sunlight to increase proteins include the feeding of plant material to chickens, hogs, and cattle. Fish farms should probably be expanded in certain areas. Intensive research should be directed toward utilizing diatoms and other sea plants as food. They can be hydrolyzed to produce sugars that can be used directly or as a means of producing edible proteins from yeast. The supply of aquatic vegetation in the oceans is enormous; and in fresh-water lakes and streams the algae and weeds should be harvested anyway because they are often a nuisance.

The utilization of farm products for local fuel is another development that can be around the corner, but the present cost of harvesting bulky, low-value products is high. If farm prices fall it may be more difficult for the farmer to pay cash for gasoline and oil for the tractors that have replaced the hay-eating horses. Wood and corn stalks and other cellulose material have been converted into alcohol—60 gallons to the ton. New developments of the Fischer-Tropsch synthesis of hydrocarbons assure us that it will be possible to convert waste organic material into carbon monoxide and hydrogen, which, with the help of iron and cobalt catalysts, can be converted into hydrocarbons and satisfactory motor fuels. Research should be directed toward developing medium-sized units for farm areas. It must be determined under what conditions part of the farm products should be used for fuel and returned to the land to improve the soil.

Some of these developments that I have suggested will come slowly, not because of technical difficulties, but because of economic circumstances. For the present, nature has supplied man with such abundant sources of fuel and food that he will not be pushed to these new things for some time unless there continues to be unequal distribution among the nations of the world due to war and political short-sightedness. It is comforting, however, to know that we can get more from the sun when we need it and that, theoretically at least, the scramble for oil and coal could be eased.

Science must go forward, regardless of immediate practical applications, accumulating a reserve stock of knowledge that can be used in any emergency. We must learn how to use our rich heritage of sunlight more efficiently so that we can be prepared against such catastrophes as war, overpopulation, exhaustion of oil and coal, and the return of the glaciers (*4*). The scientists, too, must cooperate with the social scientists and statesmen so that adequate preparations can be made for any social, economic, and political readjustments that may follow the scientific developments.

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