
SOLAR RADIATION

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This paper is an introduction to a discussion of methods of converting part of the enormous flux of solar radiation incident on the surface of the earth directly into useful energy. Until now, the human race has been content to watch natural processes change solar radiation into other forms of energy and to rely on these secondary sources for most of the power it requires. For example, the energy derived from food, coal, gasoline and other petroleum products, and electricity generated in hydroelectric power plants, was all obtained from sunlight. At present a large fraction of our energy comes from coal and oil which were produced very slowly. As we are using these stocks of energy many times faster than they are being replaced, it is becoming increasingly urgent for us to develop methods of drawing upon our current supply of solar energy for the power we need. Thus, we need to know whether it is sufficient to rely on natural processes for converting solar energy or whether it is possible to devise ways of converting solar energy directly and economically into useful power. Although this problem has been considered for many years, no method has yet been invented which can compete with present sources of power. The problem is complicated by the nature of solar radiation which is very different from any other source of power so far used. This introduction is intended to discuss the nature of solar radiation, the amount of energy available, and the amount which we can hope to convert into useful energy using presently known methods. The description of the various methods proposed is discussed by other authors.

THE NATURE OF SOLAR RADIATION

When we step out of the shade on a summer's day we are conscious of being warmed by sunlight. What does sunlight consist of and how was it formed?

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Part of the radiation from the sun is in the form of visible light which, when passed through a prism, produces a spectrum containing all the pure colors from red at one end to violet at the other. Each color in the spectrum is due to a particular type of radiation and the different colors are caused by radiation of different wave-lengths. Light is a form of electromagnetic radiation of the same nature as radio signals and consists of a rapidly alternating electromagnetic field. The product of the number of oscillations of the field per second and the wave-

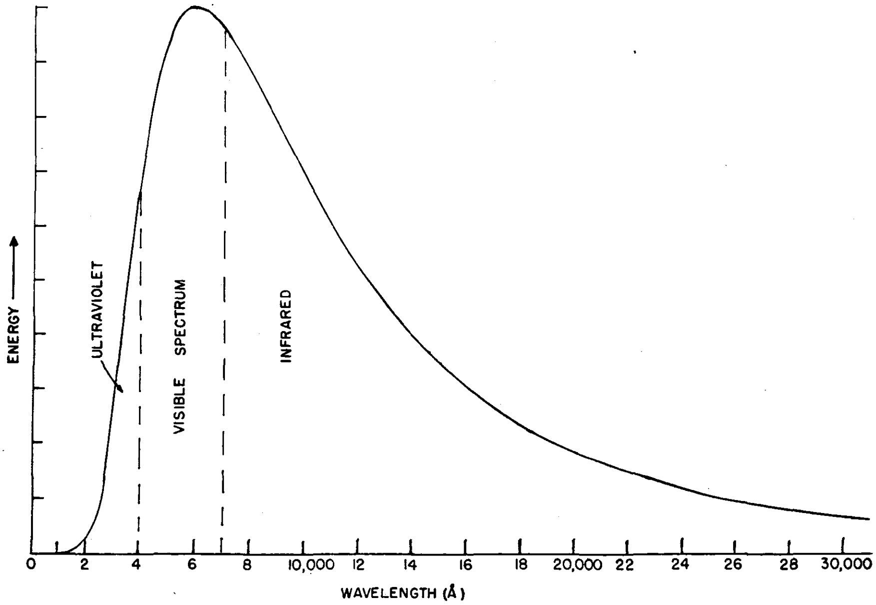

FIGURE 1. The spectral distribution of energy leaving the sun.

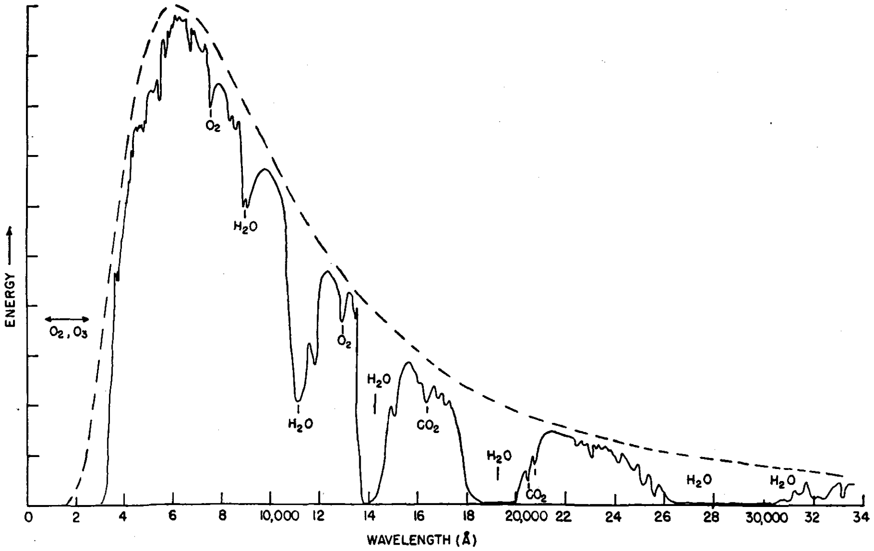

FIGURE 2. Spectral distribution of sunlight arriving at earth's surface.

length gives the velocity of the radiation. In free space this velocity is 186,000 mi./sec. for all wavelengths. The violet end of the spectrum corresponds to radiation of wavelengths about 4,000 Ångstroms (1 Ångstrom = 10^{-8} cm.), and the red end to a wavelength of about 8,000 Ångstroms. In addition, the sun also emits radiation of shorter wavelength than the violet end of the visible spectrum, called ultraviolet radiation. Beyond the red end is infrared radiation.

If the amount of energy present at each wavelength is measured, a curve can be drawn showing the energy distribution of solar radiation. This curve, shown in figure 1, has a maximum near the green region of the visible spectrum (5,000 Å.). When the solar spectrum is investigated with a spectrometer, an instrument which enables the spectrum to be examined in detail, narrow absorption lines are found throughout the whole spectrum where the energy at certain wavelengths is greatly reduced. In some cases the absorption takes place in the solar atmosphere and in others in the earth's atmosphere. Measurements made at ground level show the solar energy disappears entirely at some places in both the ultraviolet and infrared regions, due to complete absorption by the earth's atmosphere (fig. 2).

THE SUN

The temperature of the solar surface emitting radiation can be determined from the spectral distribution of sunlight. The shape of the energy curve and the wavelength position of maximum energy indicate that this temperature is about 6,000° C. To understand how the surface continues to keep so hot when it is continually radiating energy into space requires a knowledge of the physical and chemical states existing in the sun.

The sun is a great ball of intensely hot matter which, because it is so hot, must be gaseous. Its visible surface is 864,000 miles in diameter and, in volume, the sun is one and a third million times as large as the earth. Surrounding the sun is an extremely tenuous atmosphere which is usually only visible during an eclipse. The average density of the sun is about 1.4 times that of water and its mean distance from the earth is 93 million miles.

The energy given off by the sun is generated in its interior. Because this lies below the visible surface it is not directly observable, however, the temperature must increase from the 6,000° C. at the surface, to many times this value at the center. This increase is due, in part, to the gravitational forces holding the sun together, since, as the center of the sun is approached, the weight of the overlying layers increases and both the density and the temperature of the lower layers must increase to support the weight. At the center, the density is probably close to 80 times that of water and the temperature around 40 million degrees C. These high temperatures and pressures enable nuclear reactions to occur which furnish sufficient energy to keep the sun at its high temperature.

Various types of nuclear reactions have been suggested, but it is now believed that the most important one is a chain of processes in which carbon nuclei react with protons (hydrogen nuclei) to build up more complex atoms which are later decomposed to form carbon atoms again and helium nuclei. The net result of this reaction is that four protons combine to form one helium nucleus. Since the mass of the resulting helium nucleus is less than that of the four protons, mass is lost in the reaction. It is converted into radiation, following Einstein's law which states that $E = mc^2$, where m is the mass which has disappeared, c is the velocity of light and E is the energy of the radiation.

Unlike earlier ideas of the origin of the sun's energy—such as, the heat produced by chemical reactions or by the gradual contraction of the sun—the theory that mass is being converted into energy is the only one yet advanced which will, working on reasonable assumptions, account for the huge amount of radiation the sun must have emitted since its birth more than a billion years ago. From the size of the sun's surface and its temperature it is possible to calculate that mass is being converted into energy at the colossal rate of 4 million tons per second; however there is still sufficient hydrogen present for the sun to keep on emitting energy, on its present scale, for many more millions of years.

The energy produced in the interior of the sun has to find its way to the surface before it can escape into space. The normal methods of conduction or convection of heat are not rapid enough to transport the enormous amount of energy from the interior to the surface. Instead, it is believed that energy is brought to the surface by radiative processes. The atoms in the interior of the sun emit radiation which is captured by neighboring atoms and these in turn re-radiate. Thus, the radiation is trapped in the sun for a long time while it is passed from one atom to another but it eventually reaches the sun's surface and escapes. The character of the radiation changes markedly on its way to the surface. In the interior of the sun it is probably in the form of very short wavelength radiation in the X-ray region of the spectrum. As the radiation passes to the cooler outer regions, the process of absorption and re-emission gradually increases its average wavelength until, by the time the surface is reached, it is approximately in the form in which it arrives at the earth.

The surface of the sun emitting radiation is called the photosphere; it is comparatively thin, its thickness being estimated in tens of miles. When examined with a telescope the photosphere has a mottled appearance, caused by the occurrence of brilliant granules on a contrasting dark background. The granules are about 2,000 miles in diameter and have an average life of only a few minutes, indicating that they are probably caused by convection currents from hotter levels just below the surface. The edge of the photosphere is very sharply defined though its density is only about 1/10,000 that of air at sea level. It is opaque, even though it is so tenuous, because the gases of which the photosphere is composed are strongly ionized, and in this state are able to absorb and emit a continuous spectrum of radiation.

When sunspots are visible they are located in the photosphere. Sunspots appear as relatively dark regions on the surface of the sun—relatively dark because they are also at extremely high temperatures of around 4,000° C. They usually occur in groups moving from east to west across the surface indicating that the sun rotates about an axis in the same direction as the earth. The number of sunspots varies from year to year but shows a maximum about every 11 years—the well known sunspot-cycle. Much has been written about sunspots and the relations between them and phenomena on the earth. Emissions from sunspots and related phenomena have profound effects on the earth, especially the upper atmosphere, as well as affecting the electric and magnetic fields surrounding the earth. However, these emissions—astronomers and geophysicists still argue about their true nature—do not appear to penetrate in appreciable quantity to ground level, and will consequently have little bearing on a discussion concerning the utilization of solar energy.

Above the photosphere is the more or less transparent solar atmosphere which is usually seen only during a total eclipse. The region closest to the photosphere is called the reversing layer and extends for several hundred miles in height. The mean temperature in this region is appreciably lower than that of the photosphere and many of the absorption lines in the solar spectrum originate here. They are caused by atoms which absorb energy of certain wavelengths from the continuous spectrum of radiation coming from the photosphere and re-radiate it in all directions, thus weakening the original beam. In the solar spectrum these lines are only dark by comparison with the radiation of nearby wavelengths; during an eclipse, when the photosphere is hidden, they show up in the spectrum of the reversing layer as bright lines on a dark background.

Above the reversing layer is the chromosphere. This is so named because of its scarlet color caused by the emission of a strong hydrogen line lying in the red region of the spectrum. The chromosphere is several thousand miles in height and it gradually merges into the outermost solar envelope, or corona, which appears as a filmy, pearly halo of intricate structure, stretching out hundreds of thousands of miles from the sun.

Of the 92 naturally occurring elements, over 60 are known to exist on the sun, and most of the others are probably also present but in quantities too small to be detected. Although the relative abundance of metals in the sun and the earth's crust is very similar, this is not true of the non-metals, hydrogen and helium, in particular, being much more abundant on the sun.

THE EARTH'S ATMOSPHERE

The radiation leaving the sun spreads out in all directions and 93 million miles away it may or may not hit the upper fringe of the earth's atmosphere. The radiation then has to pass through the atmosphere to reach ground level. During its passage, some of the radiation is lost because of atmospheric absorption, scattering, and other processes.

Atmospheric Absorption

The earth's atmosphere strongly absorbs radiation in the ultraviolet and infrared regions of the spectrum. Fortunately, air is practically transparent to the visible region and short distances beyond the violet and the red, and so the spectral interval containing the greater portion of the solar energy can reach ground level without being seriously depleted.

Absorption in the Ultraviolet.—The gases which absorb most of the ultraviolet energy are oxygen and ozone. Oxygen is present to heights of several hundred miles above the earth's surface and as it strongly absorbs radiation of wavelengths shorter than 1750 Å. all such solar radiation has been completely absorbed by the time it has penetrated to within 50 miles of the earth's surface. An oxygen molecule can be dissociated into two oxygen atoms when it absorbs radiation of sufficiently short wavelengths. The two resulting atoms can both receive additional energy in the form of an increase of velocity, as a result of this absorption. Consequently at great altitudes, the few atoms and molecules present are moving with great velocities which are normally associated with high temperatures.

Molecular oxygen is stable below 50 miles because no radiation is available to dissociate it; and the atmosphere is cooler because it cannot absorb much solar radiation. However, the oxygen atoms formed higher up wander to lower levels where they collide with greater numbers of other molecules as the pressure increases. Under certain conditions an oxygen atom can collide with an oxygen molecule and combine with it to form ozone. This reaction occurs most frequently at heights of 15 to 30 miles above the earth and a layer of ozone is formed in this region. Ozone strongly absorbs radiation of wavelengths shorter than 3200 Å., and thus radiation which passes through the ozone layer contains no energy below 2900 Å. because of absorption by oxygen and ozone. The energy absorbed by the ozone is sufficient to produce a marked increase in the temperature of the atmosphere just above the main ozone layer.

This atmospheric absorption is responsible for the abrupt cut-off in the energy curve, shown in figure 2, and astronomers are not certain of the shape of the solar energy curve in the far ultraviolet. One of the experiments carried out with V-2 and other rockets has been the photographing of the ultraviolet solar spectrum above the ozone layer to determine how much energy is present at wavelengths shorter than 3000 Å.

Absorption in the Infrared.—Most of the remaining solar radiation penetrates to within 10 or 20 miles of the surface of the earth with little loss. However, below this height atmospheric pressure increases rapidly and some of the minor gases present in the atmosphere begin to absorb appreciable amounts of energy in the infrared region. These gases include water vapor, carbon dioxide, ozone, nitrous oxide, methane, and carbon monoxide. Since all of these gases have strong infrared bands, the solar energy reaching ground level is very deficient in energy of wavelengths longer than 20,000 Å.

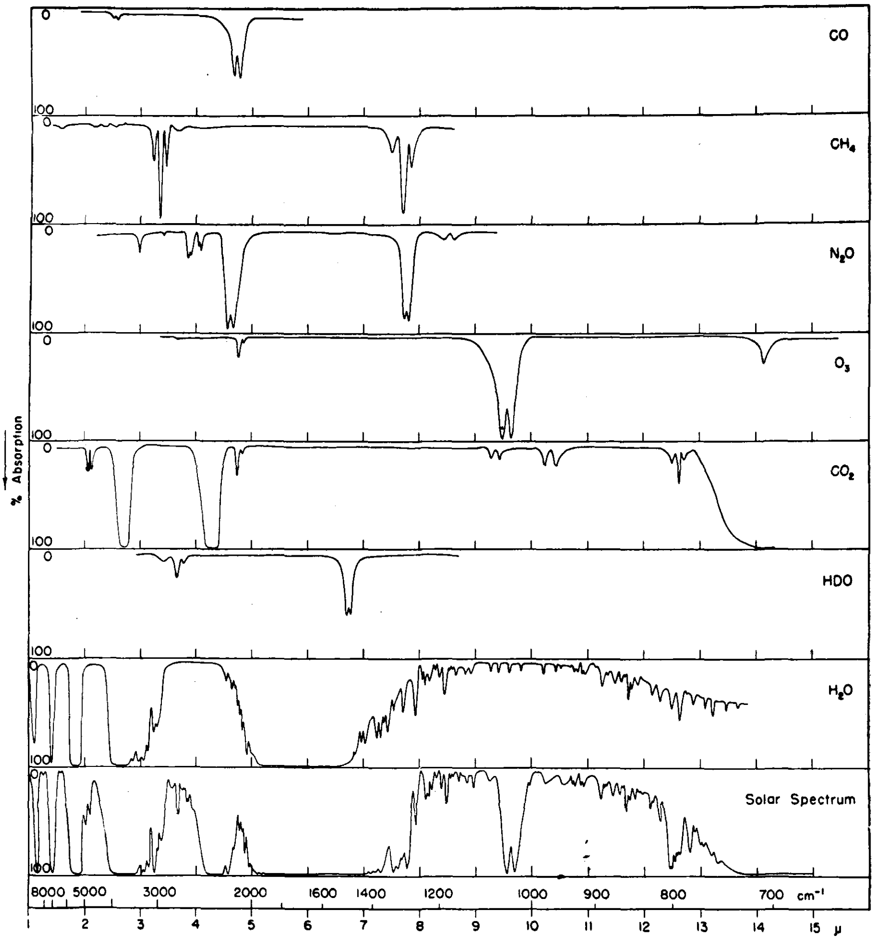

FIGURE 3. Infrared solar spectrum, from 1μ to 15μ (bottom curve), with positions and relative intensities of the bands of other known atmospheric gases shown on other curves. (1μ = 10,000 Å.)

Figure 3 shows the positions of the infrared absorption bands of the various gases. The bottom curve in this figure represents a portion of the infrared solar spectrum and shows the large energy gaps caused by these absorption bands. It can be seen that carbon dioxide and water vapor are the most important absorbers. Figure 4 shows some of the principal physical characteristics of the earth's atmosphere.

Although the atmosphere strongly absorbs in the ultraviolet and infrared, if the sun is assumed to emit radiation as a black body at 6,000° C., then 90 percent of the radiation from the sun lies between 3,000 Å. and 20,000 Å., and most of this region penetrates to ground level without being seriously depleted.

Atmospheric Scattering

Another process reducing the amount of solar energy available at ground level is known as "scattering." The molecules and dust particles in the atmosphere pick up some of the solar radiation and then act as tiny sources of light, re-radiating the energy in all directions. Only part of this re-radiated energy is sent in the direction of the original beam. The amount of light scattered by molecules is inversely proportional to the fourth power of the wavelength. Thus, blue light, which is about half the wavelength of red light, is scattered sixteen times as much. Molecular scattering is most important at the short wavelength end of the spectrum and is the reason for the blue appearance of the sky. In addition, on hazy days, light is scattered by the dust particles and droplets present in the atmosphere in a manner nearly independent of wavelength, giving the sky a hazy, milky appearance.

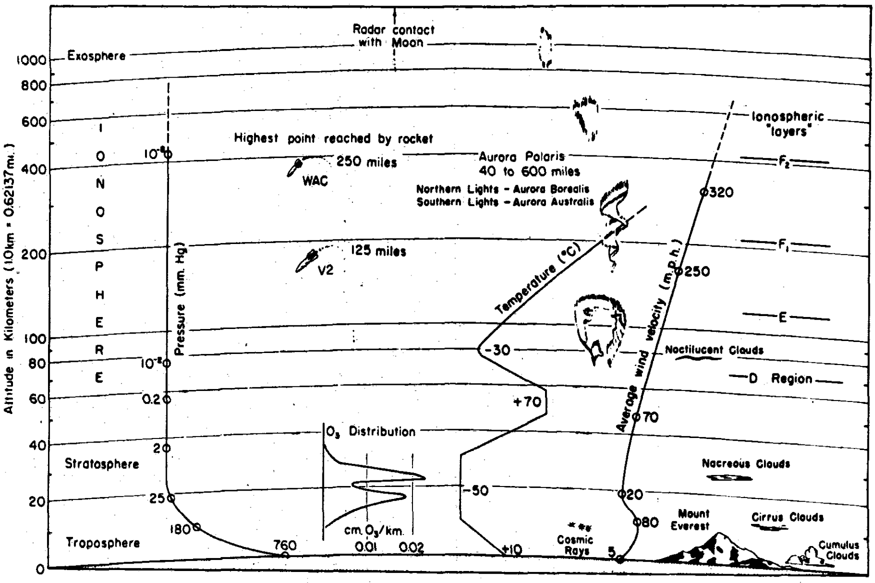

FIGURE 4. Physical characteristics of the earth's atmosphere and their variation with height; prepared from information available in 1949 by Engineering Dept., Douglas Aircraft Co., El Segundo Plant, El Segundo, Calif.

Clouds

Unless the climate is very exceptional, clouds will be present for much of the time when sunlight is available. Clouds reduce the energy reaching the ground by reflecting much of the incident energy directly into space again. The energy which penetrates thick clouds emerges from the bottom as a diffused beam because of multiple scattering by water droplets. In the process of scattering, much of the energy is also absorbed, and only a small fraction of the total incident energy reaches the ground when the sky is overcast. It should be mentioned that every thickness of cloud can occur from thin cirrostratus, which is scarcely visible and has little influence on the solar radiation, to huge banks of cumulonimbus, which absorb practically all the solar radiation.

THE AVAILABLE ENERGY OF SOLAR RADIATION

Energy is radiated from the sun at the rate of 5×10^{23} hp, so that every square yard of the sun's surface constantly emits 70,000 hp. This concentrated beam of radiation spreads out in all directions, gradually weakening with the distance from the sun and by the time it reaches the earth it is considerably reduced in intensity. The rate of arrival of solar energy, just outside the earth's atmosphere, is expressed in terms of the heat produced by the complete absorption of the radiation by a surface exposed at right angles to the beam of sunlight. The average value of this quantity (the solar constant) is about 1.94 cal./sq. cm./min. This means that energy is arriving at the rate of 1½ hp/sq. yd.—7,400 hp acre—or, the earth intercepts the equivalent in energy of burning 6 million tons of coal per second. The solar energy falling on the earth in a year is several times greater than the total energy stored in the form of oil and coal deposits.

Since all methods of using solar radiation involve the capture of energy by a surface, an acre will be taken as a convenient unit of area. An acre is 4,840 sq. yd. or roughly the size of a football field (100 yd. × 50 yd.). Although an acre exposed to the solar beam outside the earth's atmosphere receives energy at the rate of 7,400 hp, the amount reaching the earth's surface will vary with atmospheric transparency, season of the year, and time of day. With the sun vertically overhead on a clear day about 6,000 hp falls on one acre at the earth's surface.

However, the only places where the sun is ever vertically overhead lie near the equator and then the sun is in this position for a relatively short time each day. In other latitudes the amount of available energy per acre will be reduced because the sun never reaches such high altitudes. Since we are primarily interested in using solar energy in the United States, the following discussion assumes that the acre of land is situated at Columbus, Ohio, latitude 40° N., which is near the mean latitude of the United States, and the energy available per acre is calculated for this location. Other places will receive a greater or smaller amount of energy, depending on their latitude, but the difference is not large and this latitude effect will not be discussed further.

To estimate the energy which can be harvested from our acre at Columbus, the maximum energy which can be received will first be calculated and it will be shown that, for various reasons, the amount of actual available energy is greatly reduced. The figures quoted are necessarily approximate but they give the order of magnitude of the effect.

Energy Variation with Solar Altitude

When the sun is vertically overhead (90° above the horizon) energy arrives at the rate of 6,000 hp per acre; at other solar altitudes the rate at which energy arrives decreases, as shown in figure 5 and table 1. Since the solar altitude varies, it is necessary to know both the track of the sun through the sky and the length of time it is above the horizon in order to calculate the total amount of radiation falling on an acre. Both of these factors depend upon the season of the year and, consequently, the average horsepower available per acre per 24 hours varies by a factor of 4 with season, as shown in table 2. Because the losses due to atmospheric absorption and scattering depend on the path length of the radiation through the atmosphere, they will vary with solar altitude. Thus, values given in tables 1 and 2 must be further reduced to take into account these variations in energy losses and also the losses due to clouds. In addition, there are losses due to atmospheric contamination in the form of smoke and dust which vary from day to day as does the amount of cloud cover. These latter losses also vary with geographic location and, in this respect, Columbus is in a bad situation, since there are very few days when clouds are completely absent and the sky is free from haze.

For the purpose of this calculation it is assumed that the net result of all these atmospheric effects is to give an average reduction in solar energy, at all seasons of the year, of 60 percent of the values given in table 2.

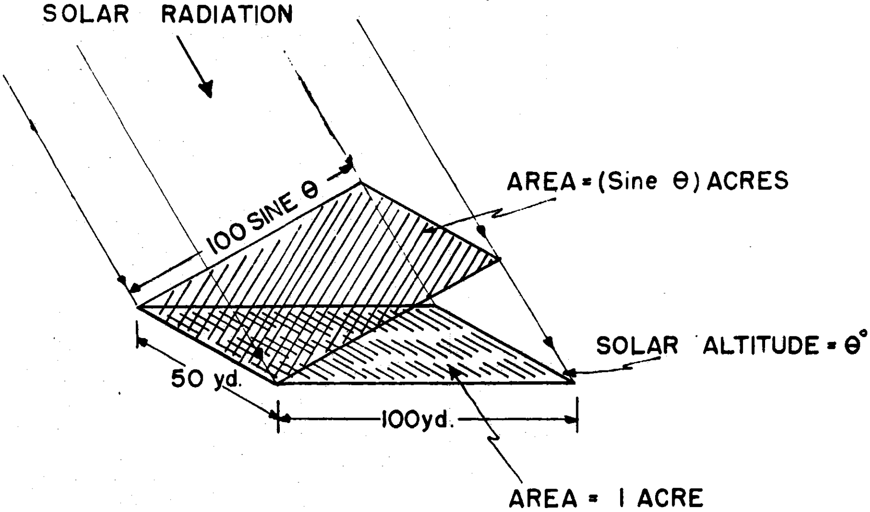

FIGURE 5. Variation in available solar radiation with solar altitude.

TABLE I
Energy variation with solar altitude

Solar altitude (Θ) above horizon	Solar energy (E) falling on 1 acre (hp) $E = E^{90°} \sin \Theta$
90°	6000
80°	5910
70°	5640
60°	5200
50°	4600
40°	3860
30°	3000
20°	2050
10°	1040
0°	0

TABLE 2
Variations in available solar energy with season

Season	Ave. solar altitude during daylight hours	Hours of available sunshine	Ave. available hp in 24 hour period
Midsummer	47°	15	2730
Spring and Autumn	32°	12	1580
Midwinter	17°	9½	700

Thus, the combined effects of the earth's rotation and the presence of the atmosphere reduce the amount of available energy per acre to the values shown in table 3, even though there is available 7,400 hp of solar energy per acre outside the earth's atmosphere.

The values given in table 3 are the ones to be used in calculating the energy crop available. To harvest this energy it must first be collected and then converted into a useful form. The methods for collecting and converting the radiation will depend on the final use of the energy. However, since any device will only convert a fraction of the incident radiation into useful energy, depending both on the theoretical efficiency of the method used and the efficiency of the actual apparatus, the final yield per acre will be much smaller than the values given in table 3.

TABLE 3

Average amount of solar energy per acre at different seasons

Season of Year	Average hp available per acre at Columbus, O., per 24 hours
Summer	1640
Spring and Fall	950
Winter	420
Yearly Average	1000

METHODS OF UTILIZING SOLAR ENERGY

There are several important factors which influence the design of apparatus for utilizing solar radiation. The most important problem is the collection of the radiation which is spread over a wide spectral interval and reaches ground level in a beam which has, for most practical purposes, a cross section of infinite area. Also, this radiation arrives in amounts which vary greatly with time.

One of the basic elements of any apparatus is a large gathering surface capable of capturing a wide spectral interval of radiation. In addition, because of the erratic nature of the radiation, the apparatus must always be ready to utilize short intervals of sunshine and should have no long "warm-up" period during which sunlight is being wasted. It must also operate efficiently when the intensity of the beam of radiation is low, as for instance, when a thin cloud bank is present, the atmosphere is very hazy or when the sun is close to the horizon. For the apparatus to be economically efficient, it must require little or no energy to keep it in working order during the time when solar energy is not available, and it should be practically automatic in operation since human attention is very expensive. Finally, for most practical uses, the apparatus must supply energy when required and not only when the sun is shining. Thus, a method of storing energy must be incorporated in the design.

These limitations impose stringent conditions on the types of methods used and also on the design of the apparatus. Other papers describe these problems in more detail and discuss ways of overcoming them. Here, the principles of the various methods proposed will be discussed and their expected efficiencies compared by making, what appear to be, reasonable assumptions. There are two main ways of using solar energy once it has been captured. These are:

(1) For space heating (e.g., houses), and

(2) For supplying energy for doing mechanical work.

The apparatus for capturing the radiation will probably be very different in these two cases.

The application of solar radiation to space heating is discussed by Professor Löf. Here, the object is to capture sufficient solar energy to be independent of other sources of heat with an apparatus as automatically efficient as a gas furnace is today, and yet at a price which is competitive with other methods of heating. Since the cost of running such a device should be negligible, the main expense will be incurred in the installation of the unit. This will depend upon the size of the space to be heated, the complexity of the apparatus, and the amount of solar radiation available.

The efficiency and the cost of any apparatus will depend on the ingenuity of its inventor, but the quantity of radiation available depends on geographic location and season of the year. Thus, while it may be economically feasible to use solar radiation for space heating in, say, Colorado, it may be entirely out of the question in Ohio. This is discussed more fully later, but it is interesting to find that a house which uses one ton of coal a month for space heating could obtain the same amount of energy from the sunshine falling on an area of 150 sq. yd., assuming that solar energy was available at the mid-winter rate of 420 hp per acre (table 3) and that the energy converter was 100 percent efficient.

The second proposed use of solar radiation is as a source of mechanical energy. The United States contains large areas of ground of little agricultural value that receive huge quantities of solar radiation. It would seem that here is an ideal source of energy. There are several different methods of trapping this supply which all utilize the quantum nature of radiation. Sunlight was described earlier as electromagnetic radiation of different wavelengths. During the last thirty years it has been shown that there is an alternative way of describing radiation by considering it to be composed of particles or photons of different energies. With each wavelength, on the classical theory, are now associated photons with fixed amounts of energy. The energy of a photon describes its spectral position and is inversely proportional to its wavelength as measured in the classical electromagnetic theory. The intensity of the radiation is measured as the number of photons in the beam. The photons can react with matter in a number of different ways, depending on their energies, and the three main types of interaction between photons and matter, which have so far been considered for utilizing solar radiation, are described below.

Photothermal Effect.—All substances irradiated with photons absorb some of them and reflect or transmit the rest, depending upon their energies. The photons absorbed disappear, but their energy is transformed and is usually used to give the atoms or molecules composing the material, a greater degree of movement which manifests itself as an increase in temperature of the body. Here, the energy of the photon has been transformed into thermal energy and hence the heading of this paragraph. A substance which absorbs all the photons hitting it is called a "black" body and is warmed more than others which reflect or transmit some of the photons they receive. In this photothermal effect the energy of the photons is "degenerated," because it is difficult to convert thermal energy into other forms of energy although the reverse process usually occurs only too readily. All surfaces warmer than their surroundings lose heat by conductive convective, and radiative processes; and any surface irradiated with sunlight will only be heated until its rate of loss of heat is equal to the rate at which energy is received.

Heat losses occur in all heat engines, but are likely to be very large in solar heat engines unless special precautions are taken, due to the large collecting surfaces required. These considerations show that there are serious objections to methods which convert solar energy into thermal energy and then to mechanical energy; and that it is necessary to look for other more efficient methods of capturing solar radiation.

Photoelectric Effect.—Under certain circumstances the energy of a photon can be transformed directly into electrical energy. An example of this phenomenon is found in the type of camera exposure meter which has a meter to indicate the light intensity. Here, the light falls on a specially prepared surface containing atoms or atomic lattices in crystals in such a state that they can absorb photons and transfer their energy to electrons. If the photons have sufficient energy, the electrons can escape from the bonds holding them in the crystal lattice. However, photons with less than a certain minimum energy (or radiation with a wavelength longer than a critical wavelength) even though there may be many of them, will not give the electrons enough energy to escape from the lattice, and this part of the radiation must be considered wasted. By careful preparation of the sensitive surface the freed electrons can be given a preferred direction of travel so that, when light is present, the ejected electrons all travel in the same direction and produce an electric current which can then be converted into mechanical energy.

Photochemical Effect.—Another interaction between photons and matter of importance to this problem occurs when the photon energy is used to complete a chemical reaction. The best example of this is photosynthesis—probably the major natural process for converting solar radiation into useful energy. The chlorophyll in green plants captures photons and uses their energy to carry out the reaction:

$$\text{carbon dioxide} + \text{water} + \text{photon energy} \longrightarrow \text{carbohydrate} + \text{oxygen}.$$

The energy of the photon has been converted into potential energy in the carbohydrate molecule ready to reappear when the above reaction is reversed and the carbohydrate is oxidized. Although photosynthesis cannot yet be carried out in a laboratory, other types of reactions, which can be artificially controlled, are known, where photons are absorbed and their energy used to carry out chemical reactions. In these processes, as in the photoelectric process, the useful photons must have a certain minimum energy before the reaction can proceed.

These three types of interaction between photons and matter represent the basic processes available for utilizing solar energy. A number of methods based on these principles have been suggested for converting solar energy into other forms, but, as mentioned earlier, no practical solution to the problem has been found. The reason is that the types of reaction now known and the techniques available are too inefficient.

To conclude this introduction, the relative efficiencies of these three basic methods will be discussed and the energy to be expected per acre per year estimated.

EFFICIENCIES OF SOLAR RADIATION MACHINES

Any solar radiation machine must: (a) absorb as much of the available radiation as possible, and (b) convert it into mechanical energy. The overall efficiency, *E*, of a solar machine is the product of these two separate efficiencies and can be defined as:

$$E = \frac{\text{Useful energy obtained}}{\text{Total energy of the incident radiation}}$$

$$\left(= \frac{\text{Radiation absorbed}}{\text{Total energy of the incident radiation}} \right) \times \left(\frac{\text{useful energy obtained}}{\text{energy absorbed}} \right)$$

Efficiency of the Photothermal Process.—Surfaces can be obtained which are almost completely black so that, under certain circumstances, the fraction

$$\left(\frac{\text{Radiation absorbed}}{\text{Total incident radiation}} \right)$$

can be made almost unity. This is attempted in measuring the solar constant. However, when the radiation is used to heat the working substance in a heat engine to a high temperature, difficulties arise. As it is impractical to spread the working substance over the entire acre, some optical device is required which will collect the radiation and concentrate it on a much smaller area containing the substance to be heated. Without describing actual methods it is safe to assume that not more than one-third of the total incident radiation will be available for the next stage—conversion into mechanical energy—unless complicated and expensive equipment is used. Losses will occur because not all the sunlight will be collected by the mirrors; some of that collected will not be concentrated on the right place; part of the energy will not be absorbed; and heat-losses are bound to occur in transferring the heated substance to the heat engine.

Further losses will occur in converting the remaining heat energy into mechanical energy. There is a physical law which enables the theoretical fraction which can be transformed to be calculated if we know the upper and lower temperatures between which the machine operates. Table 4 gives this theoretical efficiency for an engine working between various upper temperatures and a fixed lower temperature of 30° C. As the temperature difference increases, the efficiency increases, but the problems of preventing heat losses multiply rapidly and these will probably limit the upper temperatures chosen. No actual machine will operate with 100 percent of the theoretical efficiency (20 percent is usually accepted as being good).

TABLE 4

Theoretical efficiency of heat engines operating between a lower temperature of 30° C., and various upper temperatures

Upper Temp. ° C.	Efficiency $= \frac{\text{Work produced}}{\text{Energy absorbed}}$
100	20%
200	37%
300	48%
400	55%
500	61%
1000	76%

Thus, if we had a heat engine capable of using the solar radiation falling on one acre as a source of energy and it operated between temperatures of 250° and 30° C., at 20 percent theoretical efficiency, we could only expect to have energy available at the rate of 30 hp, averaged over a year. Since no such machine has been built, this figure is, of course, only an estimate. This figure is probably optimistic and it seems unlikely that it could be improved unless very expensive, and consequently uneconomical, equipment were used.

Efficiencies of the Photoelectrical and Photochemical Processes. In these processes photons are absorbed and their energy is converted into either electrical energy or stored as chemical energy. In both cases, photons with less than some minimum energy (or radiation longer than a certain maximum wavelength) are wasted because they are unable to bring about the required reaction. Thus, in calculating the efficiencies of such processes, only a fraction of the total sunlight is of any use. This fraction

$$\left(\frac{\text{Radiation absorbed}}{\text{Total incident radiation}}\right)$$

can be determined if we know the wavelength limits of the useful radiation for a given reaction and the spectral distribution of solar energy. Table 5 shows, approximately, this theoretical efficiency—assuming that all the incident solar radiation shorter than a given maximum wavelength can be used. Considering the human eye as an energy converter, this table shows that it is sensitive to a spectral interval containing about one-half of the total solar radiation energy and is thus potentially capable of transforming this amount into other forms of energy.

However, the eye, like all other radiation converters, is not 100 percent efficient. Some energy is lost because it is not absorbed, and in all photochemical and photoelectric reactions now known, very low yields are obtained because many of the photons, which are potentially useful, dissipate their energy in the "photothermal" process and are wasted in just heating the reactants.

For a comparison with the solar heat engine, a process which absorbs 50 percent of all the solar radiation in the ultraviolet and visible portions of the spectrum and converts 10 percent of the absorbed radiation into useful energy would give 20 hp per acre on the average during a year assuming that the incident energy was arriving at the average rate of 1000 hp per acre.

TABLE 5

Table showing the theoretical efficiency of a selective solar radiation absorber which can only usefully transform radiation less than a certain maximum wavelength into energy

Critical Wavelength λ Å	Eff. = $\frac{\text{Solar energy between 3000 Å and } \lambda \text{ crit.}}{\text{Total solar radiation}}$
3,000	0%
Violet	
4,000	4%
5,000	15%
6,000	26%
7,000	36%
Red	
8,000	47%
9,000	56%
10,000	64%
15,000	84%
20,000	90%

Thus, the energy derived would be less than that from the heat engine, and both figures show the extremely small amounts of energy which can be obtained; although 7400 hp per acre is incident outside the earth's atmosphere. Although all types of processes appear to give low efficiencies, it is easy to understand why the photochemical and photoelectrical processes look most promising for future work. As our chemical and physical knowledge increases, it should be possible to increase the practical efficiencies of these methods; whereas the efficiencies of heat engines are unlikely to be improved. In addition, heat engines will be expensive to install because of the complexity of the equipment required and maintenance costs will be high because of the attention they need. Chemical and electrical processes, on the other hand, should be practically automatic in operation and if cheap materials can be made to operate satisfactorily, no large installation costs need be incurred.

Thus, the problem of utilizing solar energy is not easy to solve, but there is reason to hope that ultimately solar energy will provide a cheap source of power as our other sources of energy disappear.

REFERENCES

The following review articles contain additional information and discussion on the subject and also give further references to earlier papers.

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