SOLAR ENERGY TECHNOLOGY HANDBOOK

Part A Engineering Fundamentals

Editors

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PREFACE

Solar energy, as generally defined, includes energy derived directly from sunlight as well as indirectly in the form of wind, waves, tides, ocean thermal gradients, or as fuel from biomass and other photochemical reaction products. Over the past several years there has been an explosive growth in solar energy research, development, and demonstration, particularly in the United States.

In 1972 a solar energy panel, organized by the National Science Foundation and the National Aeronautics and Space Administration, made the first comprehensive assessment of the potential of solar energy as a national energy resource.* They also examined the state of the technology in the various solar energy application areas. The total U.S. budget for solar R&D in that year was $1.7 million. In 1979 the annual U.S. solar budget had increased to $550 million and is expected to be more than $700 million in 1980.

This tremendous increase in government funding, not only in this country but in several other countries, has resulted in a proliferation of new ideas and concepts as well as a large increase in available information and data in all of the solar technologies. Hence there is a need for a comprehensive handbook describing the present state of knowledge and offering the best available information and data in each solar energy technology. It is hoped that this *Solar Energy Technology Handbook* will fulfill this requirement.

Although there may, indeed, be "nothing new under the sun," it is highly probable that in the coming years there will be technical and economic "breakthroughs" in almost all of the solar technologies covered in this handbook. New materials and new measurement techniques will be developed. There will be a continued advancement and refinement of theoretical understanding. Although a serious effort has been made by each of our contributing specialists to present the fundamentals of theory and experiment that will have enduring value, this handbook can represent only the present state of knowledge. The handbook is intended to supply the practicing engineer/scientist and student with an authoritative reference work that covers the field of solar engineering as well as peripherally related fields. References and primary citations are given to the extensive solar literature for those who wish to dig deeper.

**Solar Energy as a National Energy Resource*, Prepared by the NSF/NASA Solar Energy Panel, December 1972. Co-chairmen: Dr. Paul Donovan and Mr. William Woodward; Executive Secretary: Mr. William R. Cherry; Technical Coordinator: Dr. Frederick H. Morse; Executive Committee: Dr. Lloyd O. Herwig.

The handbook, for convenient use, is divided into eight main units: (1) The Solar Resource; (2) Solar Thermal Collectors; (3) Photovoltaics; (4) Bioconversion; (5) Wind Energy; (6) Solar Energy Storage Systems; (7) Applications of Solar Energy; (8) Non-technical Issues. In addition there are three Appendixes containing unit-conversion tables and useful solar data. It became obvious early in this project that if proper coverage were to be given each of these areas it would be necessary to divide the handbook into two volumes. The first six units constitute Part A, Engineering Fundamentals and the last two units constitute Part B, Applications, Systems Design, and Economics. These volumes have been prepared primarily as reference books, but it is felt that many of the sections will prove useful for practicing engineers, scientists, and students.

The subject of units has been a troublesome one in assembling this handbook. We were tempted to take a purist approach and insist on the strict and exclusive usage of SI units throughout. However, this did not seem practical or desirable. Since solar energy is an applied engineering technology, the use of English units (feet, horsepower, Btu, psig) is still deeply entrenched in the United States. However, the change to metric units (meters, kilowatts, joules, pascals) is well underway in all technical areas. We have attempted to soften the transition by asking our contributors to give the equivalent value in English units parenthetically after the metric value, except for the simpler units where metric is used alone. We do not claim 100 percent success in this effort, particularly in some of the tables and graphs. To make life easier for confirmed users of either set of units, a comprehensive set of conversion tables is included as Appendix A at the back of each volume.

To ensure the highest degree of reliability the cooperation of a large number of specialists has been necessary, and this handbook presents their efforts. Our heartfelt thanks go to the 58 contributors, each of whom has endeavored to present an authoritative and up-to-date overview of his/her area of solar expertise and has given willingly of very valuable time and knowledge. The editors also wish to thank Marcel and Mau Dekker, the publishers, and Graham Garratt, for their encouragement and constructive suggestions.

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unit 1

THE SOLAR RESOURCE

chapter 1

SOLAR ENERGY AND THE BIOSPHERE

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One may wonder how much of this [earth's] history could have occurred in darkness, by which I mean not merely the absence of external radiation but a much more specific thing: the absence of radiation in the range between 300 and 1,100 millimicrons. A planet without this range of radiation would virtually lack photochemistry. It would have a relatively inert surface, upon which organic molecules could accumulate only exceedingly slowly. Granted even enough time for such accumulation, and granted that eventually primitive living organisms might form, what then? They could live for a time on the accumulated organic matter. But without the possibility of photosynthesis how could they ever become independent of this geological heritage and fend for themselves? Inevitably they must eventually consume the organic molecules about them, and with that life must come to an end.

> It may form an interesting intellectual exercise to imagine ways in which life might arise, and having arisen might maintain itself, on a dark planet; but I doubt very much that this has ever happened, or that it can happen.
>
> George Wald

The sun worshipper was on the most solid of ground—without sunlight there would be nothing to give thanks for, and no one to give those thanks. The biosphere, the earth's living globe, would be a tomb instead. Without solar heat stored in the planet's crust, that crust would freeze. There would be no oceans lapping the shores and water would exist only as ice. Without solar radiation, particularly the ultraviolet, the precursors of life could not have formed. And, as Wald says, there could be no photosynthesis to convert sunlight, gas, and water into biomass.

Because there is a sun at the center of our planetary system, the earth's crust is some 250°C warmer than internal heat would keep it. Because of the sun there is water and a hydrologic cycle to erode the surface here and build it up by sedimentation there. That same water is not only a universal solvent but universal life giver as well. Ancient humans were more aware—and certainly far more grateful—of the sun's life-giving power than we are today. Through most of human history lives were sacrificed in great numbers to propitiate that power. Enlightenment has ended such brutal tributes to the sun, but along with that enlightenment we seem also to have lost appreciation for the sun as the prime mover.

The sun radiates a more or less constant 380 billion trillion (3.8×10^{23}) kw; the earth intercepts only about 170 trillion (1.7×10^{14}) kW of that prodigious outpouring. It is well that we do not receive more of this effusion. Were we the second planet rather than the third from the sun, a solar constant double our own would drive the temperature high enough to kill all life. Were we to trade orbits with Mars, the fourth planet from the sun, a solar constant less than half our input would result in an equally decisive frigid end for the earth as a living planet.

Although humanity flourishes so well in the amount of sunlight we receive that overpopulation is one of our serious problems, we swing in just about the right orbit—not too hot, nor yet too cold. And we have a constantly replenished supply of energy that is many thousands of times what we humans manage to use, and to waste.

1.1 THE SUN AND THE EARTH'S BIOSPHERE

A. The Sun

The sun is a "more or less average" star, a member of spectral type dG2. A gaseous globe with a radius of 7.0×10^5 km, it has a mass of about 2.0×10^{30} kg. This is greater than the earth's mass by a factor of about 330,000. The total rate of energy output from the sun is 3.80×10^{33} ergs/s (3.80×10^{23} kW). At a mean distance of 1.496×10^8 km from the sun, the earth intercepts about 1 part in 2 billion of this energy.

Most of the energy produced in the fusion furnace of the sun is transmitted radially as electromagnetic radiation, popularly called sunshine or solar energy. The sun radiates at an effective surface temperature of about 5800 K. The electromagnetic spectrum, comprising all the energy radiated by the sun, extends from gamma rays with wavelengths of only 10^{-11} cm to radio waves 10^5 cm and longer. This is a range of 10^{16}. The optical spectrum may be divided roughly into ultraviolet, visible, and infrared radiation. More than 99 percent of solar radiation lies within the optical range of 0.276 to 4.96 μm.

An additional, relatively small amount of energy reaches earth through the process of conduction. Energetic particles from the sun strike other particles, heat them, and they in turn heat others. Solar storms in the lower atmosphere of the sun also shoot streams of energetic particles directly from the photosphere into the atmosphere of the earth. This convective transfer of energy, and the conduction described above, account for less than a millionth of the energy radiated from the sun.

We tend to think of the biosphere as a thin envelope surrounding an isolated "spaceship earth," but this is an incomplete concept. For the earth and its biosphere may be considered as existing within the atmosphere of the sun itself, and the title of this chapter might with justification read "The Earth in the Sun's Atmosphere." In any event, we are vitally dependent on the sun's various influences.

Because the sun is wholly gaseous, it is difficult to say that its diameter is "only" 1,400,000 km. Just as the earth has an atmosphere extending many miles from its surface, and radiation fields far beyond that, the sun too has a gaseous atmosphere extending far beyond the photosphere, that "surface" layer above which density decreases appreciably. If the sun's atmosphere ends only where it has thinned to the density of interstellar space, then the earth more than likely is within the sun's atmosphere. In the vicinity of the earth the sun's atmosphere has a density of from 100 to 400 protons/cm^3. Although this is a very thin gas, it is much denser than the 0.7 hydrogen atoms/cm^3 of interstellar space. Estimates of the plasma temperature of the solar atmosphere in the vicinity of the earth are as high as 100,000 K, although the figure is misleading because the gas is so tenous that it contains little heat.

Solar gravity, for all its crushing force on the sun, is negligible in the earth's biosphere in comparison to that of the earth itself. However, the sun reaches out in other ways. The sun is the author of our weather. It provides the heat input whose variation (in ways we do not yet fully understand) causes droughts and ice ages. Varying amounts of solar radiation reaching the hemispheres also cause the seasonal changes.

Solar flares are the most spectacular disturbances emanating from the sun. The electrically charged particles emitted by some flares are a potential hazard to human life during space flight. A few such large flares occur each year; there may be as many as 100 small solar flares daily. Flares include luminous and ultraviolet radiations, and may also be accompanied by bursts of X rays, radiofrequency waves, and high-energy charged particles. These particles may have velocities as high as 100,000 km/s.

The sun also emits a plasma of electrically charged particles, consisting of 91.3 percent protons and 8.7 percent ionized helium atoms. This plasma reaches the earth, and its particles (which carry the sun's magnetic field) interact with the atmosphere and the earth's magnetic field. There is a constant outward flow of coronal gas from the sun, resulting from the high thermal conductivity of the corona. These gas particles form what is called the solar wind, which generally ranges in velocity from about 300 to 800 km/s. At times of large solar flares, however, the solar wind has been observed to increase above these values.

B. The Earth's Biosphere

Whether or not the earth itself was born of the sun, the earth's people are surely children of the sun, sired at the tremendous distance of 150 million km. The earth is a home for many billions of humans, cattle, sheep, trees, and so on. The earth's surface, ranging up and down for some 10,000 m in elevation, the air for several thousands of meters above it, and the depths of the oceans for as many thousand meters down as mountains extend up, is the biosphere or living environment. As people climb higher into space, this envelope must be extended farther from the surface of the earth. At present that distance is some 384,000 km, reaching to our lunar satellite.

The earth's atmosphere or surrounding envelope of gases is generally classified in terms of four thermal layers: troposphere, stratosphere, mesosphere, and thermosphere.

The *troposphere* extends above the surface of the earth to altitudes ranging from 8 to 16 km, depending on latitude and the season of the year. Most of the visible weather phenomena occur in the troposphere. The normal rate of temperature change in the troposphere is −6.5°C/km, and the temperature at the tropopause, or top of the troposphere, is about −60°C.

The *stratosphere* extends to about 50 km. However, the temperature increases instead of continuing to drop, and at the stratopause the temperature is about −40°C.

The *mesosphere* extends from 50 to 80 km. At its lower levels, temperature increases to a maximum of about 10°C, then decreases to about −90°C or even less, depending on latitude and season.

The *thermosphere* lies above 80 km. Here the temperature begins to increase once more and at an altitude of 400 km has reached about 320°C. Above this point temperature seems to be independent of altitude, and ranges from 750 to 1250°C under the influence of sunspots, and as high as 1700°C during solar flares.

The region of the atmosphere in which the general circulation of the air and local winds cause a more or less continuous mixing of the gaseous components is called the *homosphere*. This region, extending up to about 100 km, is made up of the following constituents by volume:

Molecular nitrogen, N_2	78.08%
Oxygen, O_2	20.95%
Argon, A	0.93%
	99.96%

These percentages are for dry air, since moisture content in the atmosphere varies from about 0.1 to 2.8 percent by volume. Carbon dioxide makes up 0.0033 percent, and the remainder includes carbon monoxide, sulfur dioxide, nitric oxide, nitrogen dioxide, water vapor, ozone, helium, hydrogen, dust, and a variety of aerosols.

Much of the solar radiation reaching the earth's outer atmosphere is reflected back into space by these constituents. Of the energy it receives, the earth reradiates mostly in the infrared; atmospheric constituents absorb much of this heat in the "greenhouse effect." As a result, air near the ground may be as much as 45°C warmer than it would otherwise be.

Above the homosphere there is little mixing of the atmosphere. In this *heterosphere,* constituents are distributed vertically in accordance with their relative masses. Heavier ones such as molecular oxygen and nitrogen are more abundant at lower levels. Atomic oxygen, hydrogen, and helium are more prevalent at the higher levels of the heterosphere. Beyond the heterosphere is the *exosphere,* or outside region. The lower level of the exosphere is thought to be from 500 to 1000 km above the earth. Here molecules or atoms no longer possess sufficient escape velocity to leave the atmosphere. Thus the exosphere is the domain of neutral particles (those without electrical charge).

The earth's magnetic field is generally thought to be caused by the dynamo action going on within the earth. The result approximates an interior dipole magnet roughly parallel with the polar axis. Because of the pressure of the solar wind, the earth's magnetic field or magnetosphere extends sunward only about 64,000 km. On the night side, it is believed that the magnetosphere extends perhaps 10 times farther. The interaction between the earth's magnetic field and the interplanetary field carried by the solar wind is complicated and not well understood. The magnetosphere is important because it deflects energetic particles from the sun, and thus protects living things from harmful effects.

The atmosphere also includes layers of charged particles. The *ionosphere* (from about 40 to 400 km above the earth) conducts electricity, and is an important factor in communications. The Van Allen belts of high-energy radiation are caused by the earth's magnetosphere. These doughnut-shaped belts, probably made up of protons and electons, girdle the earth at an altitude greater than 650 to 800 km.

1.2 LIGHT AND LIFE

Where once there was nothing but inorganic material, the earth now supports some 200 billion tons of "biomass," including green plants and a variety of animal life, at the top of which chain is man, a species presently climbing through the 4 billion population level. Man, and other animals, are properly classed as parasites, since they cannot subsist on the direct energy from the sun but must feed second-hand on plants that have already converted solar radiation into carbohydrate foodstuffs. However, animals and plants are both part of the photobiologic process. A living organism can be considered a chemical system able to maintain and reproduce itself with solar radiation. A further qualification is that in addition to being of adequate quantity, the radiation must also be of a suitable frequency.

A. Photochemistry

Sunlight, in addition to its wave motion, behaves as though composed of discrete packets of energy, called quanta or photons. Photons are a class of ultimate particles like protons and electrons. The energy of a single photon is inversely proportional to its wavelength. Thus the energy of photons of solar radiation varies widely, and photons of different wavelengths having varying effects upon matter. One mole of quanta (6.02×10^{23} quanta) is called an *einstein*. The energy content of one einstein, expressed in kilogram calories, is equal to 28,540 divided by the wavelength of the photon in nanometers.

Energy is involved in chemical reactions as energy of activation and heat of reaction. Most "dark" chemical reactions involve energies of activation between 15 and 65 kg cal/mole, corresponding to radiation wavelengths between 1900 and 440 nm. The breaking of single covalent bonds requires energies between 40 and 90 kg cal/mole, equivalent to wavelengths of 710 to 320 nm. This compares with the range of human vision. Light entering a chemical system can be absorbed, reradiated, or used to accelerate the chemical reaction. Photochemical reactions, involving the excitation of valence electrons to higher orbital levels, involve about 20 to 100 or more kilogram calories per mole, or wavelengths of 1430 to 280 nm.

Photochemical reactions include the formation of free radicals, electron transfer, intramolecular rearrangement, photoisomerization, photoionization, photoconduction in solids, and photosensitized decomposition of unexcited molecules. There are also photophysical processes such as fluorescence and phosphorescence. Both the formation of free radicals and the transfer of electrons are possible mechanisms for the conversion of solar energy for use as fuel. The Hill reaction demonstrates that oxygen is produced from water when chloryphyll-bearing plants are illuminated. Experiments have shown that some ferrous solutions when illuminated acquire an electrical potential between the illuminated liquid and the dark portion.

B. Photobiology

Photobiology (vision, phototropism, photosynthesis) proceeds at much the same energy levels as photochemistry but is confined to the slightly narrower band from about 1100 to 320 nm. Radiations below 300 nm are inimical to large, highly organized molecules such as proteins and nucleic acids. Such short wavelengths tend to open up hydrogen bonds and disrupt van der Waals attraction, thus destroying the orderly nature of the molecular arrangement. Proteins are denatured and nucleic acids depolymerized by such action. How this is prevented in nature is a fascinating story.

A great concern about the environment today is the effect that humanity is having upon it. Such interaction is not new at all but began with the appearance of life on the earth, however long ago that occurred. It is generally believed that the primordial atmosphere contained little oxygen (and thus little ozone), and very little carbon dioxide. Without these radiation screens and the additional shielding of water vapor, much more of the solar radiation spectrum reached the earth's surface. This was largely in the infrared and hard ultraviolet. Early life forms may have risen out of organic molecules whose synthesis and interaction were activated by the energetic ultraviolet. In an anaerobic environment, these forms must have existed through processes of fermentation. The resulting carbon dioxide migrated from the oceans into the atmosphere and began to change its composition.

In time, the process of photosynthesis began to make use of carbon dioxide, fixing it into organic material. Oxygen was produced; it too migrated into the atmosphere and through the photochemical processes produced a high layer of ozone. With carbon dioxide, oxygen, ozone, and water vapor now filtering out both extremes of solar radiation, the environment became more favorable for the existence of life outside the protective liquid of the oceans.

Solar radiation arrives at the outer atmosphere in a spectrum ranging from about 225 to 3200 nm. However, the ozone layer in the upper atmosphere absorbs strongly at 320 nm and is virtually opaque at 290 nm. At the other end of the spectrum, infrared beyond 2300 nm is absorbed almost completely by ozone, carbon dioxide, and water. What reaches the surface of the earth ranges from 310 to 2300 nm. Below the surface levels of the oceans, infrared is removed almost immediately, so that the radiation reaching living creatures is a narrow band centered at about 475 nm, in the blue. It is this spectral quality, as well as the quantity, of solar radiation that makes possible the photobiologic processes.

C. Vision

Visible light covers that portion of the solar radiation band between about 380 and 760 nm, although the range of human vision can be extended by different means from about 310 to 1050 nm, approximately doubling the range. As a vertebrate, man has developed image-resolving organs of vision. Two of the other 10 primary divisions of the animal kingdom have also developed such organs. These are the arthropods, including insects, crabs, and spiders; and the mollusks, including octopi and squids. It is remarkable that each has developed an entirely independent type of eye, differing as to anatomical, embryological, and evolutionary factors. Despite this uniqueness, however, each eye type uses practically the same photochemistry in its visual process. In each case, light is absorbed by the same pigment. This is retinene, the aldehyde form of vitamin A.

In the visual process, light stimulates receptors which in turn formulate and pass on a representation of the object seen. The nervous structures acted upon are ready to discharge, and light serves merely as a trigger mechanism.

Experimental work has indicated that the near infrared to about 1050 nm can stimulate vision as well as a sensation of heat. Subjects report feeling a momentary sensation of heat along with the flash of light. At the other extreme of visible light, ultraviolet is generally excluded from human sight. This is so because of the yellow pigmentation of the lens of the eye, a condition that increases with age. Yellow absorbs ultraviolet, and only those who have lost their natural lenses in cataract operations receive ultraviolet radiation at the retina, artificially extending their vision to about 310 nm in that portion of the spectrum.

So sensitive are the "rods" (the visual receptors principally involved in night vision) that a single quantum of light can trigger a reaction in them. To prevent a constant flickering of random points of light on the retina, the eye contains inhibitors that require a threshold of simultaneous absorptions in rods. This threshold appears to be at least 5 quanta.

An indication of the great range of the eye in handling visible radiation is the fact that animals that in the dark-adapted state can see by starlight can also accommodate to the light of the noonday sun. The latter represents a brightness some billion times greater than starlight.