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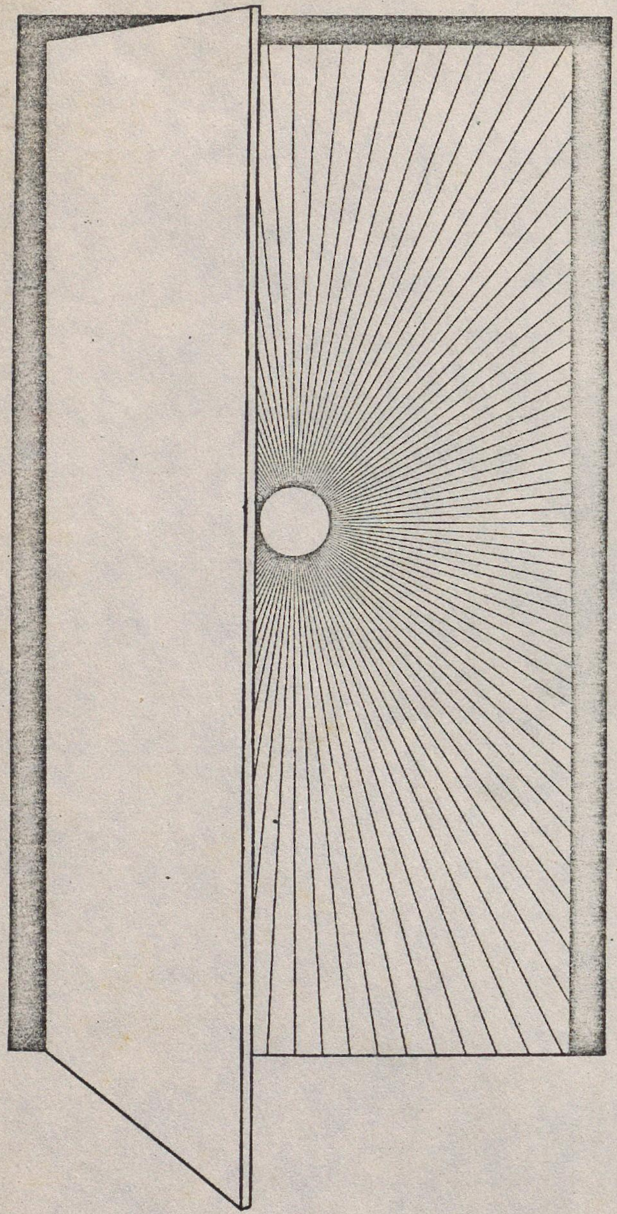

ENERGY PRIMER

SOLAR, WATER, WIND, AND BIOFUELS

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FRONT COVER
Photo courtesy of the High Altitude Observatory and NASA. *Sun's hot outer atmosphere, or corona, color-coded to distinguish levels of brightness, reaches outward for millions of miles. A coronagraph, one of Skylab's eight telescopes, masked the sun's disk, creating artificial eclipses. It permitted 8½ months of corona observation, compared to less than 80 hours from all natural eclipses since use of photography began in 1839.*

BACK COVER
Graphic courtesy of Sandicker Studios, Mountain View, California.

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Abstract: *The* **Energy Primer** *is a comprehensive, fairly technical book about renewable forms of energy — solar, water, wind, and biofuels. The biofuels section covers biomass energy, agriculture, aquaculture, alcohol, methane, and wood. The focus is on small-scale systems which can be applied to the needs of the individual, small group, or community. More than ¼ of the book is devoted to reviews of books and hardware sources. Hundreds of illustrations and a dozen original articles are used to describe the workings of solar water heaters, space heaters and dryers, waterwheels, windmills, wind generators, wood burning heaters, alcohol stills, and methane digesters. The final section of the book focuses on the need for energy conservation and some of the problems and potentials of integrated energy systems.*

QUANTITATIVE DATA ON SOLAR ENERGY

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Introduction

Current awareness of the energy crisis has generated a large volume of effort towards the direct conversion of solar energy for practical applications. Quantitative data on available solar irradiance is an essential input parameter for design of collector systems and for computing their efficiency. The spectral distribution of this energy is also important since all collecting devices in general and solar cells in particular are spectrally sensitive, and computation of total solar irradiance at ground level requires integration over all wavelengths of the spectral irradiance curve. Precise measurement of total and spectral irradiance at ground level, at each location all year round, is extremely laborious. This paper will attempt a brief survey of quantitative data on solar energy which is currently available and show how such data can be adapted for use in specific situations.

Extraterrestrial Solar Energy

Two quantities of prime importance in this regard are the solar constant and the extraterrestrial solar spectrum. The solar constant is the amount of energy incident on unit area exposed normally to the sun's rays at the average sun-Earth distance, in the absence of the Earth's atmosphere. The extraterrestrial solar spectrum is the distribution of this energy as a function of wavelength. The currently accepted values of the solar constant and solar spectrum are those published by the American Society of Testing and Materials as the ASTM Standard E 490-73a (Ref. 1). They also form the Design Criteria for NASA space vehicles (Ref. 2).

The value of the solar constant is 1353 W/m² (in the preferred SI units). Expressed in other units which are perhaps more familiar in engineering applications, the value is 1.940 cal/cm²/min, or 429.2 Btu/ft²/hr, or 125.7 W/ft², or 1.81 horsepower/m². The estimated error of this value is ± 1.5 percent. The extraterrestrial solar spectrum can be presented either as a table of values at discrete wavelengths or as a spectral curve as shown in Fig. 1 (identified as Air Mass Zero Solar Spectrum). These values are based on measurements made by different observers, mainly from high altitude jet aircraft. References 3 and 4 should be consulted for detailed information on the derivation of the ASTM standard.

The solar constant is defined for the average sun-Earth distance. As the Earth moves in its annual elliptical orbit around the sun the total solar energy received varies by ± 3.5 percent. There are also small and undetermined variations due to cyclic or sporadic changes in the sun itself. These variations are more significant in certain portions of the spectrum than in others.

Solar Irradiance at Ground Level

Solar energy conversion systems are mostly on the ground. The variability of the energy incident on a ground-based collector is considerably greater than that of the extraterrestrial energy. On days of clear sunshine the energy varies between zero before sunrise and after sunset to a maximum at solar noon. At any moment clouds may intercept the sun and decrease the energy to a low value, that of the diffuse sky radiation. There is also the variation with the seasons of the year; the amount of direct solar energy received on a horizontal surface is least during winter and greatest during summer.

The solar energy received on a surface has two components, that received directly from the sun and that diffused by the sky. A spectral curve of the direct solar radiation is shown in Fig. 1. It is labelled Air Mass One Solar Spectrum. The spectral irradiance values for this curve were computed from those of the extraterrestrial spectrum by taking into account the energy scattered or absorbed by the atmosphere. It is assumed that the sun is at the zenith (air mass is one); the surface is normal to the sun's rays; the atmosphere is one of high clarity; the total amount of ozone is 0.34 cm; and the amount of precipitable water vapor is 2 cm. The total direct solar energy transmitted by the atmosphere in this case is 956.2 W/m² or 70.7 percent of that received above the atmosphere. As solar zenith angle (the angle between the sun's rays and the local vertical) increases, the transmitted energy decreases. Table I gives data on total irradiance at ground level on a surface exposed normally to the sun's rays, for four values of solar zenith angle, and for four levels of atmospheric pollution or turbidity. The effect of pollution is expressed by two parameters α and β of the equation

$$E_\lambda = E_\lambda^\circ e^{-c_\lambda m} \quad \text{where } c_\lambda = \frac{\beta}{\lambda^\alpha} \tag{1}$$

Here E_λ and E_λ° are respectively spectral irradiance at wavelength λ after and before transmittance through a turbid atmosphere, and m is the air mass. The values of Table 1 take into account also other factors of atmospheric attenuation, which are ignored in Equation (1), namely Rayleigh and ozone scattering and molecular absorption. The partition of energy between the UV, visible and IR ranges of the spectrum is also shown. It is significant that as air mass increases or turbidity increases, the relative amount of energy in the IR increases and that in the visible and UV decreases.

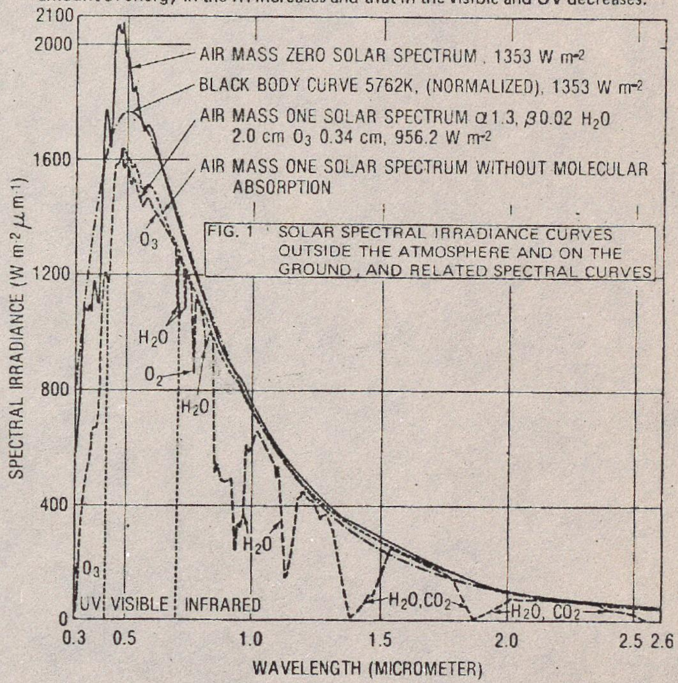

FIG. 1 SOLAR SPECTRAL IRRADIANCE CURVES OUTSIDE THE ATMOSPHERE AND ON THE GROUND, AND RELATED SPECTRAL CURVES

Direct solar irradiance (I_{DN}) discussed above is for a surface normal to the sun's rays. For a horizontal surface or a surface with any other slope, the energy received per unit area is $E_s = E_n \cos \theta$, where θ is the angle between the solar rays and the surface normal. For optimum efficiency of the collector plate, it is advantageous to have low values of θ, especially around solar noon when the air mass is least. For year round operation a surface facing south with a slope equal to the latitude of the place is desirable. For winter heating, but no air conditioning, a greater slope is desirable and for summer heating (of swimming pools, for example) a smaller slope is indicated.

Direct solar irradiance is the major term in the total irradiance on a surface. The next most important term is the diffuse radiation due to the sky. It is available always during day time, even when direct solar radiation is intercepted by clouds. A quantitative treatment of the subject is difficult because of the highly variable parameters of the atmosphere. A representative figure for diffuse sky irradiance on a horizontal surface is between one-fifth and one-sixth of the direct solar irradiance. If the surface is not horizontal but sloping at an angle T to the horizontal, the diffuse sky irradiance is related to that on a horizontal surface by the approximate ratio $\cos^2 (T/2)$.

Another major area where precise quantitative prediction is desirable but almost impossible is the solar energy available at any location over an extended period of time and the relative number of days of sunshine, cloud or rain. "As unpredictable as the weather" is a common expression; statistical data based on previous measurements will have to serve as a guide for the future. An estimate of the energy available at 61 different locations may be made from Fig. 2. It is from Reference 5, Chapter 16, where monthly averages of the daily total insolation are also available for these locations. Station 4, Inyokern, CA, has the maximum value of 569 cal/cm² per day (2381 joules/cm² per day) and Seattle University, Station 24A, has the minimum value of 269 cal/cm². These values of annual means of daily insolation should not be confused with what will be available on any given day and location. Measurements made at Goddard Space Flight Center, Greenbelt, Maryland in suburban Washington, D.C. gave values well outside this range on two consecutive days, 175 cal/cm² on May 13, 1971 and 647 cal/cm² on the next day. Daily total insolation has a wider range of

AIR MASS	SOLAR ZENITH ANGLE (DEGREES)	TURBIDITY FACTORS α	β	TOTAL IRRADIANCE W m⁻²	RATIO OF TOTAL IRRADIANCE TO SOLAR CONSTANT %	FRACTION OF THE TOTAL ENERGY IN THE UV, λ<0.4μm %	VISIBLE 0.4μm<λ<0.72μm %	INFRARED λ>0.72μm %
0	0			1353.0	100.0	8.7	40.1	51.1
1	0	1.30	0.02	956.2	70.7	4.8	46.9	48.3
4	75.5	1.30	0.02	595.2	44.0	1.23	44.2	54.5
7	81.8	1.30	0.02	413.6	30.6	0.35	39.4	60.3
10	84.3	1.30	0.02	302.5	22.4	0.102	34.7	65.2
1	0	1.30	0.04	924.9	68.4	4.6	46.4	49.0
4	75.5	1.30	0.04	528.9	39.1	1.04	42.1	56.9
7	81.8	1.30	0.04	342.0	25.3	0.26	35.9	63.8
10	84.3	1.30	0.04	234.5	17.3	0.065	30.3	69.6
1	0	0.66	0.085	889.2	65.7	4.7	46.4	48.9
4	75.5	0.66	0.085	448.7	33.2	1.14	42.4	56.5
7	81.8	0.66	0.085	255.2	18.9	0.30	36.3	63.4
10	84.3	0.66	0.085	153.8	11.4	0.08	30.7	69.2
1	0	0.66	0.17	800.2	59.1	4.5	45.4	50.1
4	75.5	0.66	0.17	303.1	22.4	0.88	38.3	60.6
7	81.8	0.66	0.17	133.3	9.85	0.14	30.0	69.8
10	84.3	0.66	0.17	63.4	4.69	0.039	22.9	77.1

TABLE 1 SOLAR IRRADIANCE ON UNIT AREA EXPOSED NORMALLY TO THE SUN'S RAYS, COMPUTED FOR DIFFERENT AIR MASS VALUES, U. S. STANDARD ATMOSPHERE, 2cm OF H_2O AND 0.34cm OF OZONE.

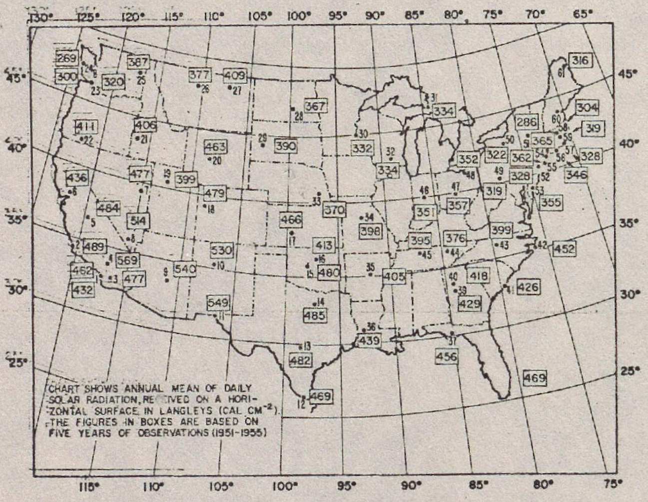

FIG. 2 ANNUAL MEAN OF DAILY INSOLATION RECEIVED ON A HORIZONTAL SURFACE AT 61 LOCATIONS IN CONTINENTAL UNITED STATES

variation from day to day at any one location than the yearly averages of such totals from one location to another. It is also instructive to compare these values with the extraterrestrial solar irradiance.

An area of one cm² exposed normally to the sun's rays outside the atmosphere at the mean sun-Earth distance would receive in 2 hours and 19 minutes the same amount, 269 cal/cm², as the average for Seattle University for a whole day. In most areas of the south-west U.S. the daily insolation is considerably greater than in the north-west. Not all locations in the U.S. are equally cost-effective in solar energy conversion. The increased cost of a collector on a synchronous satellite which has been often discussed in the news media should be weighed against the highly variable and low level solar irradiance at ground locations.

Detailed information on solar energy available on the ground can be obtained from the National Oceanic and Atmospheric Administration (NOAA) which maintains an extensive network of stations. Ninety of these belong to the solar radiation network. There is also a "sunshine switch" network with over 160 stations. Efforts are now being made by NOAA to upgrade and expand the national network for monitoring solar irradiance at ground level. The respository and distribution center for information about solar irradiance data is the National Climatic Center, Federal Building, Ashville, NC 28801.

Conclusion

The Earth-atmosphere system receives energy from the sun at the prodigious rate of 5.445 x 10^{24} joules or 1.513 x 10^{18} KW-hrs per year. The total output of all man-made energy producing systems in the world in 1970 was less than 0.004 percent of this, 2 x 10^{20} joules. Of this energy 35 percent was produced in the United States, and all but 4 percent from a rapidly dwindling supply of fossil fuels (which after all are stored solar energy). Using today's solar energy for today's needs is a challenge greater than the conquest of space. Knowing how much solar energy is available is part of meeting this challenge.

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