The Solar Resource

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1 Introduction: Basic Properties of the Sun

The sun is class G2-V yellow dwarf star of radius 6.95508 x 10^7 km and surface area of 6.087 x 10^{22} cm^2. It emits radiation produced by the internal conversion of matter into radiation into the entire 4-pi steradian solid angle (sphere), with the sun at the center. The mean radiation intensity, or radiance of the solar surface is 2.009x10^7 watts per square meter per steradian (Wm^{-2}sr^{-1}), or a total of 2.845x10^{26} watts. The Earth's orbit is elliptical with an eccentricity of 0.0167 (1.4710x10^9 km at perihelion, 1.5210x10^9 km at aphelion). At the mean Earth-Sun distance, the sun subtends a solid angle of 9.24 milliradians or 0.529°. Thus the sun is not truly a point source, and the rays from the sun are not truly parallel, but diverge into a cone with half angle of about 0.529°. At the mean distance of the Earth from the sun of 1.495979 x 10^9 km, the solar radiation reaching the top of the Earth's atmosphere is 1366.1 Wm^{-2} ± 7.0 Wm^{-2} or 1.959 calories cm^{-2} minute^{-1}.2

The Earth's elliptical orbit causes the distance between the Earth and the Sun (the Earth's radius vector) to vary by 3.39% from perihelion (closest) to aphelion (farthest). These variations in distance cause the intensity of solar radiation at the top of the atmosphere to vary as 1/R^2, where R is the radius vector. Thus the solar input at the top of the atmosphere varies from 1414 Wm^{-2} (in December) to 1321 Wm^{-2} (in July). Additional variations in solar intensity, or brightness, result from the solar sunspot cycle, and even solar oscillations. These slight variations in the solar output are usually accounted for in the calculation of solar energy available at the top of the atmosphere, or the total extraterrestrial solar radiation, referred to as ETR. The ETR has only been monitored from space since the early 1970's, or almost three solar sunspot cycles. Excellent histories of ETR measurements and analysis are provided in Frohlich^3 and Gueymard.4
2 The Spectral Distribution of the Sun as a Radiation Source

In this chapter we briefly describe the solar spectral distribution, or distribution of energy with respect to wavelength, over the region of the electromagnetic spectrum of use to renewable energy systems. The sun radiates energy at wavelengths ranging from the X-ray and gamma ray spectral region out into the very long wavelength radio spectral region. We will restrict our discussion, for the most part, to solar energy in the wavelength region between the ultraviolet (UV) of wavelength 250 nanometers (nm) and the near infrared (NIR) with wavelength of 4000 nm or 4.0 micrometers.

The Planck theory of blackbody radiation provides a first approximation to the spectral distribution, or intensity as a function of wavelength, for the sun. The blackbody theory is based upon a "perfect" radiator with a uniform composition, and states that the spectral distribution of energy is a strong function of wavelength and is proportional to the temperature (in units of absolute temperature, or Kelvin), and several fundamental constants. Spectral radiant exitance (radiant flux per unit area) is defined as:

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M(\lambda) = \frac{2\pi c^2 h}{\lambda^5 \left( e^{\frac{hc}{\lambda kT}} - 1 \right)}
\]

where \( \lambda \) is wavelength (in meters), \( h \) is Planck's constant = 6.626196x10\(^{-34} \) Joule seconds (J s), \( c \) is the velocity of light in vacuum = 2.9979250x10\(^{8} \) meter per second (ms\(^{-1} \)), \( k \) is Boltzman's constant = 1.3806x10\(^{-23} \) Joule per Kelvin (J K\(^{-1} \)), and \( T \) is absolute temperature in Kelvins.

The sun is not a "perfect" radiator, nor does it have uniform composition. The sun is composed of about 92% hydrogen, 7.8% helium. The remaining 0.2% of the sun is made up of about 60 other elements, mainly metals such as iron, magnesium, and chromium. Carbon, silicon, and most other elements are present as well.\(^1\) The interaction of the atoms and ions of these elements with the radiation created by the annihilation of matter deep within the sun modifies and adds structure to the solar spectral distribution of energy. Astrophysicists such as Kurucz have used quantum calculations and the relative abundance of elements in the sun to compute the theoretical spectral distribution from first principles.\(^5\) Figure 1 shows a plot of the Kurucz computed spectral distribution at very high resolution (0.005 nanometer at UV) as well as an inset showing much lower resolution (0.5 nanometer in UV to 5 nm in IR) plot.

Figure 2 is a plot of the low resolution ETR spectrum compared with the Planck function for a blackbody with a temperature of 6000 Kelvin. The differences in the infrared, beyond 1000 nanometers are small. The larger differences in the shortwavelength region are due to the absorption of radiation by the constituents of the solar composition, resulting in the "lines" observed by Fraunhofer and named after him.