SOLAR IRRADIATION FUNDAMENTALS

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Contents

Summary

Among the renewable and environmentally friendly energy sources Sun's radiation plays the most significant share, which is not yet fully developed but has the highest potential in the future as heater, photovoltaic and especially solar-hydrogen energy alternatives. In particular, solar energy systems are recognized as a primary technology in the medium and long-term energy sources, which is capable to reduce global warming effects and climate change impacts also. It is, therefore, necessary a good understanding of the fundamentals of the solar irradiation with its astronomic, meteorological and geographic features for proper modeling studies, potentially feasible locations, sustainability prior to any innovative instrument and technological improvements and developments for the service of future human demands. The key issues for the further applications of solar energy technology, engineering analysis and modeling lie in the proper understanding of solar radiation fundamentals.

According to the aforementioned significance of the solar energy source an overview on the solar irradiation fundamentals are presented in this chapter.

1. Introduction

Energy is in a continuous conversion from one type to another. Various conversions appear continuously or intermittently, which imply scientifically that there is energy conversion in terms of energy balance in the evolution of any natural or artificial phenomenon. It is possible to visualize that energy conversion and conservation are among the most significant features that dominate the possibility of continuous alteration features in atmosphere, lithosphere, hydrosphere, biosphere and cryosphere. These various spheres imbed accumulation, distribution, transmission, conversion, conservation and movement of energy and consequently human beings seek to abstract energy for their benefits from such spheres. Hence, there is a continuous stage of open energy chain in nature, which is clean and does not expose significant damage to the environment. This brings to the mind about the initial source of energy and subsequent conversions. No doubt, the unlimited source is the Sun, which depreciates itself for the service and satisfaction of the energy needs in the universe.

The source of almost every type of energy is the solar irradiation in the form of electromagnetic radiation (EMR) waves that reach the Earth surface. Present Earth is almost 4.5 billion years of age and since then its surface and subsurface compositions have changed continuously and there are numerous hidden paleo-surfaces that were functional at various stages of geological epochs. In addition to tectonic movements, natural burial of paleo-surfaces are partially due to wind and water movements that obtain energy from the Sun. Coal, oil, asphalt and natural gas remnants are different types of energy sources and they are deposits of biomass from time immemorial. Due to their burials they are referred to as fossil fuels, which were once active in the atmosphere, hydrosphere and biosphere. These readily available deposits and their rather easy conversions into practically usable energy types gave rise to extraction and exploitation in unprecedented rates since a century. On the contrary, fossil energy usage means the return of polluting gases, especially carbon dioxide (CO_2), into atmosphere and hence atmospheric chemical composition changes, which show undesirable implications in the weather and climate events even leading to present climate change (global warming, greenhouse effect) impacts.

Since the global energy crisis in 1973 many countries started to seek clean and renewable energy resources for future use with research and development activities. Such activities have increased unprecedented in recent years and it is expected that this trend will continue even in an increasing rate in the coming decades.

Energy policy should help to guarantee the future supply of energy and regulate the necessary conversions and replacements of fossil energy sources with renewable alternatives. International cooperation on the climate change issue is a prerequisite for achieving cost-effective, fair and reasonable solutions for future sustainability. At the focus of all renewable energy alternative sources is the Sun’s radiation, which is an undeletable energy source for future generations.

2. The Sun

Sun plays dominant role since geological time scale immemorial for different natural activities in the universe at large and in the Earth at particular concerning the formation of fossil and renewable energy sources. It will continue to do so until the end of the Earth's remaining life, which is predicted as about 5 billion years. Deposited fossil fuels that are used through the combustion are expected to last circa 300 years at the most in the form of coal, but then onwards the human beings will be confronted to remain with the renewable energy resources only apart from nuclear energy.

The diameter of the Sun is 2R = 1.39x10^6 km, it is an internal energy generator and distributor for other planets such as the Earth. It is estimated that 90% of the energy is generated in the inner zone between 0 and 0.20R, which contains 40% of the Sun mass and it is referred to as the core. The core material temperature varies between 8x10^6 ^{o}K and 40x10^6 ^{o}K and the density is estimated as about 100 times that of water. The radiation zone extends from 0.2R to 0.7R, which is comparatively cooler than the core. At a distance 0.7R from the center, the temperature drops to about 130,000 ^{o}K, where the density is about 70 kg/m^3. Finally, the convection zone as the outer cover of the sun extends from 0.7R to 1.0R with temperature of about 5,000 ^{o}K and the density 10 $^{-5}$ kg/$m^{3.}$ Figure 1 shows a representative form of all three stages.

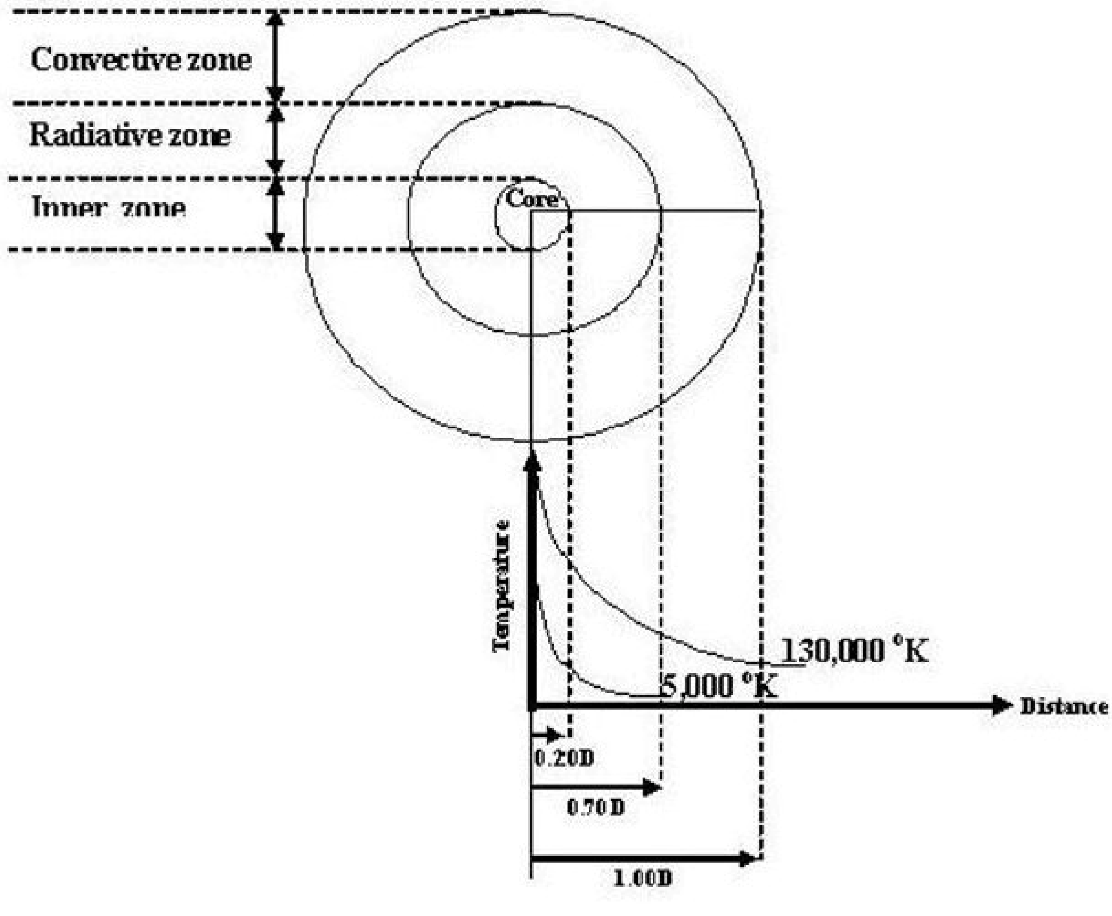

Figure 1. Sun layers

The observed surface of the Sun is composed of irregular convection cells with dimensions of about 1,000 - 3,000 km and with cell life time of a few minutes. Small dark areas on the solar surface are referred to as pores, which have the same order of magnitude as the convective cells and larger dark areas are sunspots at various sizes. The outer layer of the convective zone is the photosphere with a density of about 10^{-4} that of air at sea level. It is essentially opaque as the gases are strongly ionized and able to absorb and emit a continuous spectrum of EMR. The photosphere is the source of most solar radiation. There is the recessing layer above the photosphere with cooler gases of several hundred kilometers deep. Surrounding this layer is the chromosphere with a depth of about 10,000 km, which is a gaseous layer with temperatures somewhat higher than that of the photosphere but with lower density. Still further out is the cornea, which is a region of very low density and very high temperature (about 10^6 ^oK). The solar radiation is the composite result of abovementioned several layers.

An account of the Earth's energy sources and demand cannot be regarded as complete without a discussion of the Sun, the solar system and the place of the Earth within this system. In general, the Sun supplies the energy absorbed in short terms by the Earth's atmosphere and oceans, but in the long terms by the lithosphere where the fossil fuels are embedded. Conversion of some of the Sun's energy into thermal energy drives the general atmospheric circulation (Becquerel, 1839). A small portion of this energy in the atmosphere appears in the form of kinetic energy as winds, which in turn drive the ocean circulation. Some of the intercepted solar energy by the plants is transformed virtually by photosynthesis into biomass. In turn, a large portion of this is ultimately converted into heat energy by chemical oxidation within the bodies of animals and by the decomposition and burning of plants. On the other hand, a very small proportion of the photosynthetic process produces organic sediments, which may eventually be transformed into fossil fuels. It is estimated that the solar radiation intercepted by the Earth in 10 days is equivalent to the heat which would be released by the combustion of all known reserves of fossil fuels on Earth.

Sun can be regarded as a huge furnace in which hydrogen atoms fuse into helium at immensely high temperatures. The Sun is a big ball of plasma composed primarily of H (70%) and He (27%) and small amounts of other atoms or elements (3%). Plasma is a space where the electrons are separated from the nuclei because the temperature is so high and accordingly kinetic energies of nuclei and electrons are also high. Protons are converted into He nuclei plus energy by the process of fusion. Such a reaction is extremely exothermal and the free energy per He nuclei is 25.5 eV or $1.5x10^8$ (kcal/gr). The mass of four protons 4x1.00723 is greater than the mass of the produced He nucleus 4.00151 by 0.02741 mass units. This small excess of matter is converted directly to EMR and is the unlimited source of solar energy. The source of almost all renewable energy is the enormous fusion reactor in the Sun, which converts H into He at the rate of $4x10^6$ tones per second. The theoretical predictions show that conversion of four H atoms (i.e. four protons) into the He using carbon nuclei as catalyst will last about 10^{11} years before H is exhausted. The energy generated in the core of the Sun must be transferred towards its surface for radiation into the space. Protons are converted into He nuclei and because the mass of the helium nucleus is less than the mass of the four protons, the difference in mass (around $5x10^9$ kg/sec) is converted into energy, which is transferred to the surface where electromagnetic radiation and some particles go off into space, which is known as solar wind (Şen, 2008).

Sun radiates EMR energy in terms of photons which are light particles. Almost one-third of this incident energy on the Earth is reflected back, rest is absorbed, and eventually retransmitted to deep space in terms of long-wave infrared radiation (Section 5). The total power that is incident on the Earth's surface from the Sun every year is

1.73×10^{14} kW and this is equivalent to 1.5×10^{18} kWh annually, which is equivalent to 1.9×10^{14} ton coal equivalent (tce). Compared to the annual world consumption of almost 10^{10} tce, this is a very huge and unappreciable amount. It is approximately about 10,000 times greater than what is consumed on the Earth annually. This energy is considered as uniformly spread over the Earh's surface and hence, the amount that falls on one square meter at noon time, is about 1000 W in the tropical (equatorial) regions (Section 7.3.1). The amount of solar power available per unit area is known as irradiance or radiant-flux density. This solar power density varies with latitude, elevation and season of the year in addition to time in a particular day as in Figure 2.

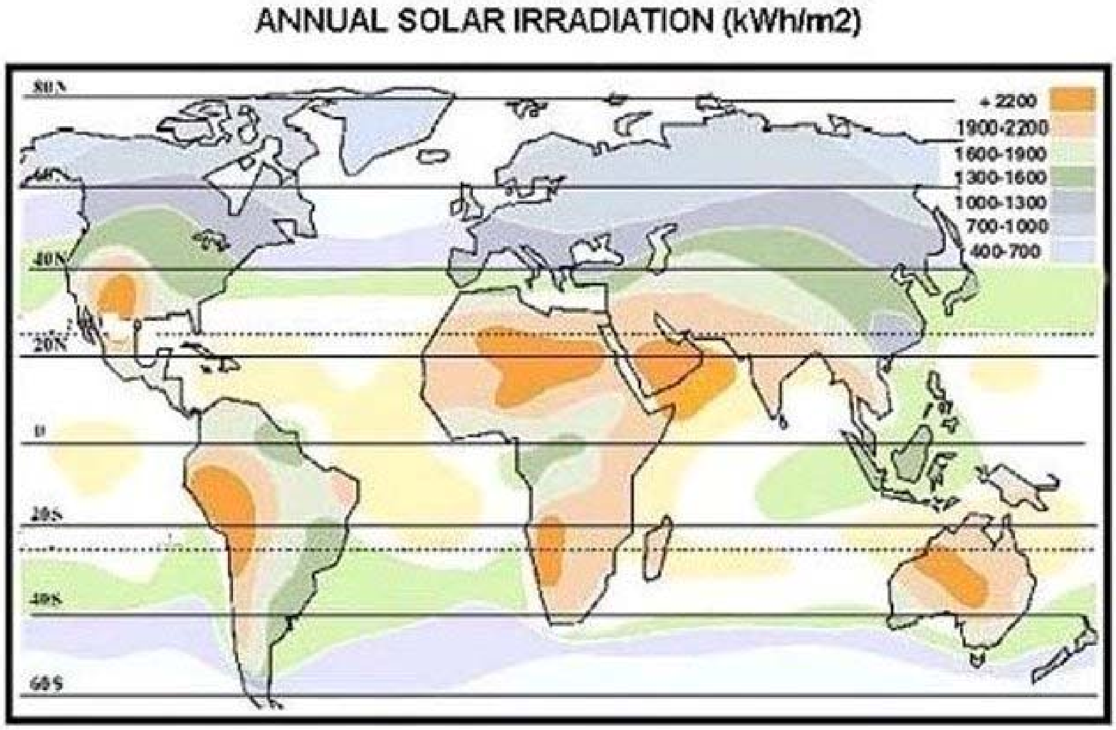

Figure 2. Global solar irradiation distribution

A horizontal surface immediately under the Sun would receive 1360 W/m^2. Along the same longitude but at different latitudes the horizontal surface receives smaller solar radiation from the equator towards the polar region. If the Earth rotates around the vertical axis to the Earth-Sun plane, then any point on the Earth surface receives the same amount of radiation throughout the year. However, Earth rotates around an axis which is inclined with the Earth-Sun plane, and therefore, the same point receives different amounts of solar irradiation in different days and times in a day throughout the year (Section 4). Hence, seasons start to play role in the incident solar radiation variation. Additionally, diurnal variations are also effective due to day and night succession. An important feature is the absence of seasons at the tropics and the extremes of six-month summer and six-month winter at the poles, (Dunn, 1986).

Most of the developing countries lie within the tropical belt of the world where there are high solar power densities, and consequently, they want to exploit this source in the most beneficial ways. On the other hand, about 80% of the world's population lives between latitudes 35^{o}N and 35^{o}S. These regions receive Sun radiation for almost 3,000 to 4,000 hours per year. In solar power density terms, this is equivalent to around 2,000 kWh/year again tce as 0.25. Additionally, in these low latitude regions, seasonal Sunlight hour changes are not significant. It means that these areas receive Sun radiation almost uniformly throughout the whole year.

The practical applications and beneficial use of the solar radiation require consideration of practical and engineering aspects, where the efficient and sustainable use of the solar energy comes into view. For instance, in any design of solar energy powered device, it is necessary to know how the power density will vary during the day (Section 5), from season to season, and also the effect of tilting a collector surface at some angle to the horizontal (Section 9.3).

3. Atmospheric Effects and Electromagnetic Radiation (EMR) Spectrum

The atmosphere drives almost 100% of its energy from the Sun. Briefly, radiation is the transfer of energy through matter or space by electric or magnetic fields suitably called electromagnetic waves. High energy waves are emitted from the tiniest particles in the nucleus of an atom, whereas low energy is associated with larger atoms and molecules. Highest energy waves are known as radioactivity since they are generated by the splitting (fission) or joining (fusion) of particles and low energy results from vibration and collision of molecules. The solar radiation is partially absorbed by matter of increasing size, first by exciting electrons as in ionization and then by simulating molecular activity at lower energy levels. The latter is sensed as heat. Hence radiation is continuously degraded or dissipated from tiny nuclear particles to bigger molecules of matter.

EMR propagates automatically in the space as a ubiquitous phenomenon originating from the Sun. EMR radiation from the Sun is described by its wavelength, λ, (distance from peak to peak of the wave) and frequency, f, (number of cycles per second). As wave moves by a location its speed, c, can be expressed as,

$$c=\lambda f \qquad (1)$$

The spectral distribution of the solar radiation in W/m^2 per micrometer of wavelength, that is, it gives the power per unit area between the wavelength range of λ and $\lambda+1$, where λ is measured in micrometers, μm (Figure 3). The area under the curve gives the total power per square meter radiated by a surface at the specified temperature. The solar spectrum is roughly equivalent to a perfect black body at a temperature of 5,800 ^{o}K. After the combined effects of water vapor, aerosol, dust, and adsorption by various molecules in the air, certain frequencies are strongly absorbed and as a result the spectrum received by the Earth's surface is modified due to air mass, AM, as shown in Figure 3. A detailed account of AM is presented in Section 7.3.2.

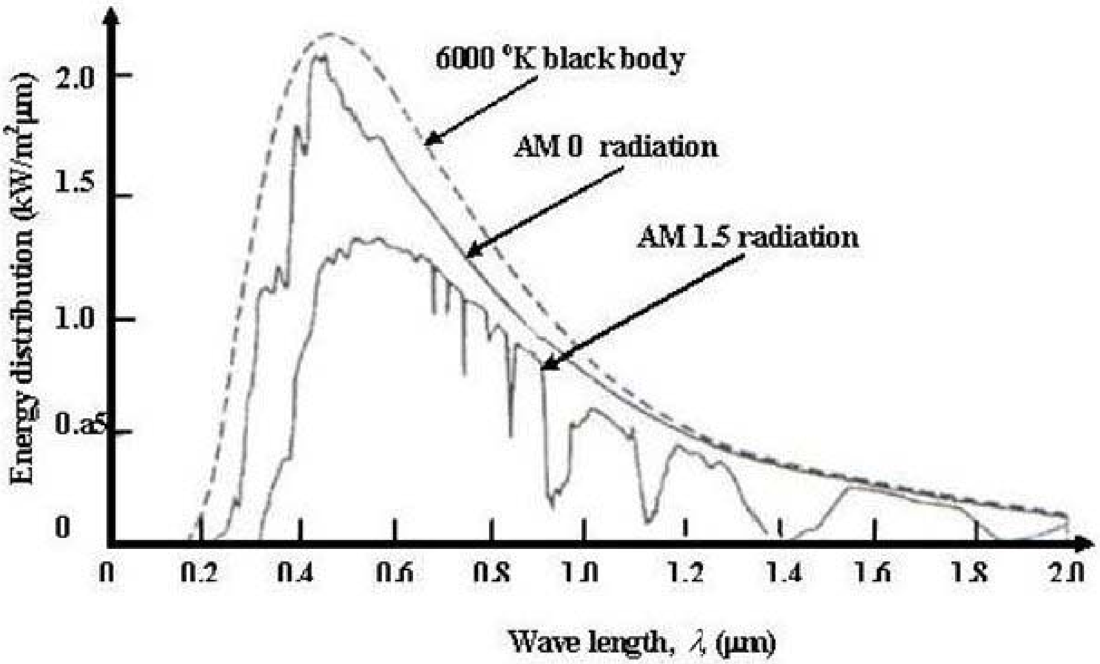

Figure 3. Solar spectrum

As it can be seen from the same figure the maximum solar irradiance is at about the wavelength λ = 0.5 µm, which is in the region of the visible solar radiation from λ = 0.4 µm to 0.7 µm (Figure 4).

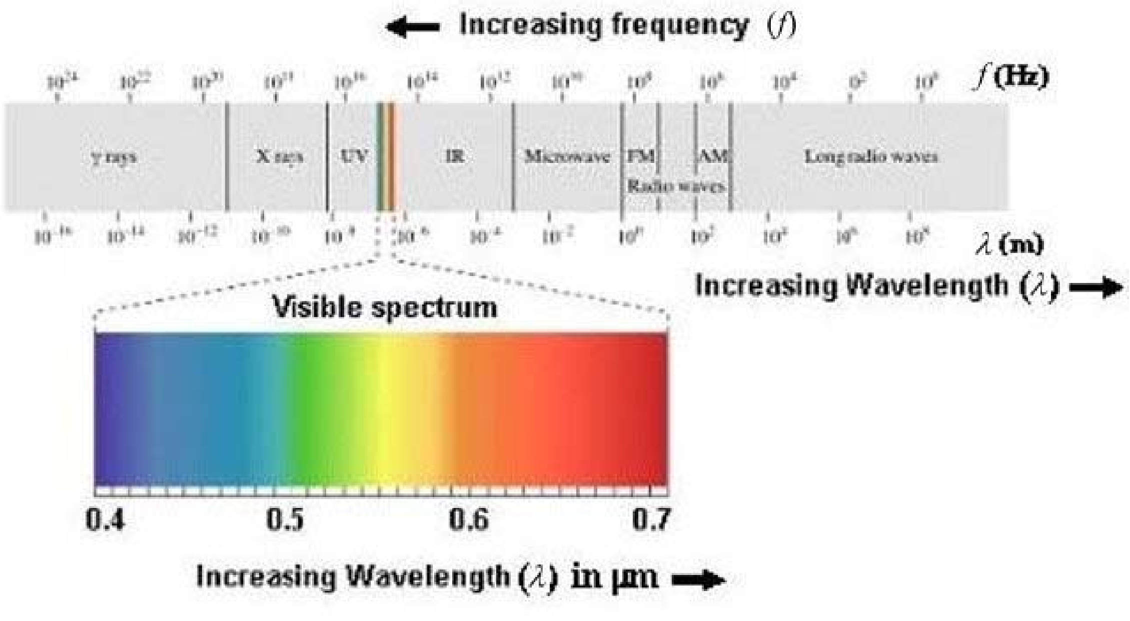

Figure 4. Visible spectrum

EMR spectrum contains wavelengths, which are too long to be seen by the naked eye (the infra-red) and also wavelengths, which are too short to be visible (the ultra-violet). The range of the visible spectrum is very small with red light having a longer wavelength (0.7 μm) than blue light (0.4 μm). In nature any rainbow is a familiar example of few color mixtures from the spectrum, whereas white light is just a superposition (mixture) of all the colors. There are detectors for the whole range of EMR and for instance with an infrared detector, it is possible to see objects in the dark.

Details of EMR waves are also shown in Figure 4 as radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma (γ) rays. The most practical significance of EMR is its carriage of energy and momentum that may be imparted to matter through three types of interaction, namely, conduction, convection and radiation.

The Earth receives its radiation from the Sun at short wavelength around a peak of 0.5 μm, whereas it radiates to space at a much lower wavelength around a peak value of 10 μm, which is well into the infra-red. EMR waves show particle properties as photons, and in particular, they behave as if they were made up of packets of energy, E, which is related to frequency f as,

$$E = hf \qquad (2)$$

where h is the Plank constant, $h = 6.626 \times 10^{-34}\,\text{Jsec}$. Planck (1901) determined the relationship between the radiative energy flux emitted from a blackbody and its absolute temperature. Planck's law states a complex (and non-linear) relationship between the energy flux per unit wavelength, the wavelength and the temperature. Two useful derivatives of this law are the Wien law, which states the relationship between the wavelength corresponding to the maximum energy flux output by a blackbody and its absolute temperature. The relationship between the maximum power radiated wavelength $\lambda_{\max}$, and the body temperature, T, is given as Wien's law (Collares-Pereira and Rabl, 1979),

$$\lambda_{\max} = 3x10^{-3}T^{-1} \qquad (3)$$

where $\lambda_{\max}$ is given in μm, T is in units of ^{o}K. On the other hand, the Stefan-Boltzmann law, which shows the relationship between absolute temperature and the total energy flux, I, emitted by a blackbody, over the entire wavelength range can be written as follows,

$$I = \sigma T^{4} \qquad (4)$$

where I is in units of W/m^2, T is in units of ^{o}K, and σ is a constant equal to $5.67 \times 10^{-8}\,\text{W m}^{-2}\text{K}^{-4}$.

The EMR spectrum is the range of radiation from very short wavelengths (high frequency) to very long wavelength (low frequency) as in Figure 5. The subsections of

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Biographical Sketch

Prof. Dr. Zekai Şen, He has obtained B. Sc. and M. Sc Degrees from Technical University of Istanbul, Civil Engineering Faculty, Department of Reinforced Concrete in 1972. His further post-graduate studies were carried out at the University of London, Imperial College of Science and Technology. He was granted Diploma of Imperial College (DIC) in 1972, M. Sc. in Engineering Hydrology in 1973 and Ph. D. in stochastic hydrology in 1974. He worked in different countries such as England, Norway, Saudi Arabia and Turkey. He worked in different faculties such as the faculty of Earth Sciences, Hydrogeology Department; Faculty of Astronautics and Aeronautics, Meteorology Department. His main interests are hydrology, water resources, hydrogeology, hydrometeorology, hydraulics, science philosophy and history. He has published about 300 scientific papers in almost 50 different international top journals on various following topics.

Water Sciences; Renewable Energy; Hydrology; Hydraulic; Earth Sciences; Hydrogeology; Rock Mechanics; Engineering Geology; Atmospheric Sciences; New and Renewable Energy Sources;

Hydrometeorology; Climatology; Modeling of Air Pollution; Mathematical Statistical; Stochastic processes; Chaotic behaviors; Fractal Geometry; Geostatistics; Kriging Methods; Fuzzy Logic; Genetic Algorithms; Artificial Neural Network.

He has written many books in Turkish, one book in Arabic and English books are published in 1995 and 2008 by CRC Lewis Publishers with titles “Applied Hydrogeology for Scientists and Engineers” and "Wadi Hydrology", respectively; and another book in 2008 by Springer-Verlag with title "Solar Energy Fundamentals and Modelling Techniques (Atmosphere, Environment, Climate Change and Renewable Energy)". He has supervised many M. Sc. and Ph. D. degrees including about 10 international Ph. D. students from different disciplines and countries. He holds several national and international scientific prizes and the most recent one is given as a team work due to his contribution to "Nobel Peace Prize" through his works in IPCC 2007. Another two international books under publication are "Spatial Modeling in Earth Sciences", which will appear in May 2009 and "Fuzzy Logic and Hydrologic Modeling" in August 2009. He is currently working at the Technical University of Istanbul, Civil Engineering Faculty. He is also the president of Turkish Water Foundation.