AVAILABILITY OF SOLAR RADIATION AND ITS ESTIMATION

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Contents

Summary

Solar energy is spread out and is available in all places around the world. Its intensity varies significantly according the place on the earth's surface and for the same place according to the time of the day, the time of the year and the existing meteorological conditions. It is very spread out, in dilute concentration, As a very important renewable energy source solar radiation parameters and solar-earth angles are of importance for the estimation of the energy reaching the earth's surface.

1. Introduction

Solar energy is emitted in huge amounts from the sun's surface but only a fraction of that reaching the earth's surface can be converted into useful forms of energy for utilization either as thermal, electrical or mechanical. For desalination purposes solar energy can be used either directly to distill water in solar stills or can be utilized indirectly to drive conventional desalination plants. In indirect use of solar energy solar radiation has to be collected and converted into either heat or electricity. The transformed solar radiation can then be applied to drive one of the conventional desalination systems. Thus in an indirect utilization of solar energy two separate plants are involved: a solar thermal or electricity plant and the desalination plant. Collectors or concentrators are used to convert the radiation into thermal energy in the form of hot water or steam. The steam generated is of low or high temperature, depending from the type of the solar collector field. Low and medium temperature steam is used as process heat in industry, including desalination plants, or as space heating. Electricity is produced either by high temperature steam in solar power systems or by solar cells in photovoltaic fields.

The irregularity of solar radiation intensity affects the normal and smooth operation of the desalination plants, which operate in a discontinuous and unsteady state basis if storage is not provided. Storage devices are necessary for continuous operation, during night time or during cloudy days, but are also capital intensive enterprises adding to the already high cost of solar energy conversion systems. Although there are these disadvantages, thermal solar energy systems are suitable for providing energy to medium or small size desalination plants in sites where there is abundant and intensive solar radiation. Normally all solar powered plants offer energy, at a reasonable cost, suitable to use in desalination facilities.

Solar energy may be available in some form everywhere but it is not available at all times anywhere on the earth. To determine whether and how solar energy is available and, or, usable on an economic basis precise meteorological data must be known, and all data concerning the incident solar radiation of the region.To operate all solar plants and desalination solar systems, the spatial and the temporal, i.e. the hourly, daily and seasonal, variability data of solar radiation is of importance These data are also indispensable for the proper design of a solar driven system, and for the proper selection of devices and methods to be used. Their most important utilization is in the evaluation of the performance of both plants. A detailed understanding of the spatial, temporal and the spectral characteristics of the solar radiation is attained through detailed and exact measurements, detailed analysis of the data selected, and computer modeling of the variations in solar radiation. It is thus very important for an engineer dealing with solar desalination to know all about the sun and its global radiation emitted around the year.

2. The Sun and the Radiation Emitted

2.1. The Physics of the Sun

The sun is a sphere consisting of intensively hot ionized gaseous matter, called plasma. In fact the sun is a large nuclear reactor where thermo-nuclear fusion reactions take place continuously generating huge amounts of energy. The energy radiated into the surrounding space is characterized by the sun's structural characteristics. These principal characteristics (Sayigh 1984) are:

Linear diameter	1.392×10^6 km
Sphere mass	$(1.991 \pm 0.002)\times10^{30}$ kg
Average mass density	$(1.410 \pm 0.002)\times10^3$ kg m^{-3}
Effective blackbody surface temperature	5762 ± 50 K
Interior temperature	8×10^6 to 40×10^6 K
Average distance from earth	$1.495\times10^6 \pm 1.7\%$ km
Core density	100×10^3 kg m^{-3}
Surface density	~ 10^{-5} kg m^{-3}
Solar energy at the Earth atmosphere	178×10^{14} kW
Time for the ray to reach Earth	8 min

The linear diameter corresponds not directly to the real diameter, as the sun's atmosphere extends far beyond the photosphere, with decreasing density. The thermonuclear processes that take place in the mass of the sun lead to the production of radiation particles called photons. In the vicinity of the earth the atmosphere of the sun has 100×10^6 to 400×10^6 protons per m^3 and about 0.7×10^6 hydrogen atoms per m^3. Photons are energy units having zero charge and no mass. The energy of a photon E is proportional to its frequency and the Planck's constant, h (with numerical value = 6.6×10^{-34} J).

$$E = h\times\nu = \nu\times6.6256\times10^{-34}\,J \qquad (1)$$

The photon energy increases with frequency increase, i.e. increases with decreasing of the corresponding wavelength. When the thermonuclear processes are in progress in the sun, molecules, atoms and electrons are raised to excited states and then momentaneously return to low energy states releasing thermal energy known as electromagnetic radiation. It is estimated that about 90% of the energy emitted is generated in the region of 0 to 0.23 of its radius, a region where about 40% of the sun's mass is concentrated. The energy released from the core is transferred upwards, in the form of X-rays and γ-rays, to the upper zone of the sun near the surface. This zone consist of an opaque strongly ionized gas layer, called "photosphere", which absorbs and emits a continuous spectrum of radiation. It is the source of light and heat radiated to the earth.

2.2. The Electromagnetic Spectrum

The colossal fusion that takes place in the sun' mass releases tremendous quantities of electromagnetic radiation, as result of its mass fusion. Calculations derived from Einstein's mass-energy conversion equation, $E = mc^2$, have shown that the sun loses 4×10^9 kg s^{-1}, or 0.5×10^{-21} of its total mass per second. This amount of mass is released as energy and it is distributed into space in the form of electromagnetic radiation. Its spectrum varies from very short wave length cosmic radiation to very high frequency long wavelength radiation, i.e. from fractions of Ångstrom (10^{-10} m) to hundreds of meters. The spectrum is divided into wavelength bands which travel into space with the speed of light, *c*, and is connected to the wavelength λ and the frequency ν by the following simple equation:

$$c = \lambda \times v = 2.99776 \times 10^{8}\,\mathrm{m\,s^{-1}} \qquad (2)$$

The approximate wavelength bands are given by Robinson (1966) as follow:

10 Å X and γ rays	7200 Å-1.5 μm near infrared
10-2000 Å	Far ultraviolet 1.5-5.6 μm middle infrared
2000-3150 Å	Middle ultraviolet 5.6-1000 μm far infrared
3150-3800 Å	Near ultraviolet > 1000 μm micro
3800-7200 Å	Visible region radio-waves

The spectrum between 2000 and 30 000 Å carries 98% of the total emitted energy and it is called the "quiet sun" region. The temperatures in this region are 8×10^{6} to 40×10^{6} K. Wave lengths greater than 30 000 Å, belong to the infrared region and are absorbed by water vapor and carbon dioxide in the atmosphere. In the ultraviolet region wavelengths of approximately 2860 Å reach the sea level but shorter wavelengths are absorbed by the ozone layer in the upper regions of the atmosphere. The solar radiation that reaches the earth's surface consists of wave lengths of the ultraviolet to near infrared range, i.e. from 0.3 to 2.5 μm. For most solar applications the radiation in the visible range (0.38 to 0.78 μm) and the near infrared (0.78 to about 2 μm) is of most importance.

The sun is considered as a black body, thus the total radiation emitted per unit area from its outer surface, the photosphere, is calculated from the Stefan-Bolzman equation:

$$G_s = \sigma \times T^4 = 5.67 \times 10^{-8} (5762)^4 = 62.50 \times 10^3 \ \mathrm{kWm^{-2}} \qquad (3)$$

Wavelength range λ [μm],	0-0.38	0.38-0.78	0.78-40
Approximate energy W m^{-2}	95	640	605
Approximate % of total energy	7.0%	47.3%	44.7%

Table 1. The solar energy spectrum distribution (Mangal 1990).

Taking in consideration the total surface of the sun, for $D_s = 1.392\times10^{9}$ m, the total power emitted by the sun is given as:

$$\pi \times (D_s)^2 \times G_s = 3.14159 \times (1.392 \times 10^9)^2 \times 62.50 \times 10^3 = 3.8046 \times 10^{23} \ \mathrm{kW} \qquad (4)$$

Out of this amount the earth intercepts only 1.78×10^{14} kW. The amount of electromagnetic radiation emitted from the sun in the main wavelength regions is given in Table 1.

3. The Extraterrestrial Radiation

3.1. What is the Solar Constant

The incident spectral solar radiation outside the earth's atmosphere is called "extraterrestrial", G_o, or, air-mass zero (AMO) solar radiation. Its instantaneous power the "irradiance" or, solar flux density is measured in W per square meter (W m^{-2}**)** and is considered as a constant, although there exist some fluctuations due to solar activities. At the top of the atmosphere and at a mean earth-sun distance r_o, the intensity of this radiation is termed as the "Solar Constant", G_{sc}, which is defined as: "the perpendicular radiation that receives a surface of one square meter, at the earth's mean distance from the sun per unit of time". Many scientists give in their studies values of the Solar Constant, calculated from terrestrial measurements. Today most measurements are performed in extraterrestrial space by satellites.

NASA (1971) performed extraterrestrial measurements by spacecraft and as a result the exact value of the solar constant was calculated as $G_{sc} = 1353 \pm 0.021$ W m^{-2}, or 4.871 ± 75.5 kJ m^{-2} h^{-1}. Later measurements by Iqbal (1983) give a value for the solar constant of 1367 W m^{-2} or 4.921 MJ m^{-2} h^{-1}. Today solar constant values are derived from satellite and spacecraft measurements with differences less than 1.0 per cent. The World Radiation Center (WRC) adopted the Iqbal value accepting an uncertainty of 1.0 per cent. It is the value of solar constant accepted by the most scientists in their scientific work.

3.2. Variations of the Extraterrestrial Radiation

The earth has an elliptical orbit that results in approximately *a* ± 3.3% variation in the amount of solar radiation at the top of the atmosphere throughout the year. For a plane, *p*, outside the atmosphere, at a distance, *r*, from the earth, the extraterrestrial radiation is given as: $G_o = G_{sc}(r_o/r)$. The extraterrestrial intensities for the 21st of each month of the year are presented in Table 2. They can be also calculated from a set of equations as a function of the sun's angles, which are defined in (Section: Flat-plate collectors). The extraterrestrial solar radiation and the solar constant are the initial imput data for the solar radiation calculations that receive solar collectors. They are used to formulate equations for the scattering and the absorption processes taking place in the atmosphere and also to calculate the "Clearness Index". The extraterrestrial radiation G_o is calculated as a function of the solar constant and a random day of the year from Eqs (14) and (15) given below.

3.3. The Black-body Emittance and Absorptance

The sun acts as an effective radiation blackbody, independent of the incident directions. A perfect absorber is also a perfect emitter of radiation, thus it emits the maximum possible radiation. It has to absorb and emit all spectral radiation maintaining a constant temperature. The blackbody is an imaginary concept, because no real material is a perfect absorber or emitter. Nevertheless some materials, mainly black in color, approach the blackbody characteristics having an absorptance or emittance of about 99 per cent.

Month	**Q_o (W m^{-1})**	**Month**	**Q_o (W m^{-1})**	**Month**	**Q_o (W m^{-1})**
January	1422	May	1344	September	1367
February	1401	June	1333	October	1390
March	1387	July	1334	November	1411
April	1364	August	1345	December	1423

Table 2. Extraterrestrial solar radiation intensities normal to the sun on the 21st of each month (Sayigh 1986)

The blackbody energy distribution curves shown in Figure 1, are presented by three curves for temperatures of 5000, 6000 and 7000 K. The total radiation in the shaded curve corresponds to the so called "smoothed" solar curve which lies in the visible wavelength region. The spectrum of this curve is cut off on the ultraviolet side, below the 6000 K curve, in the infrared region, its maximum being at 4700 Å.

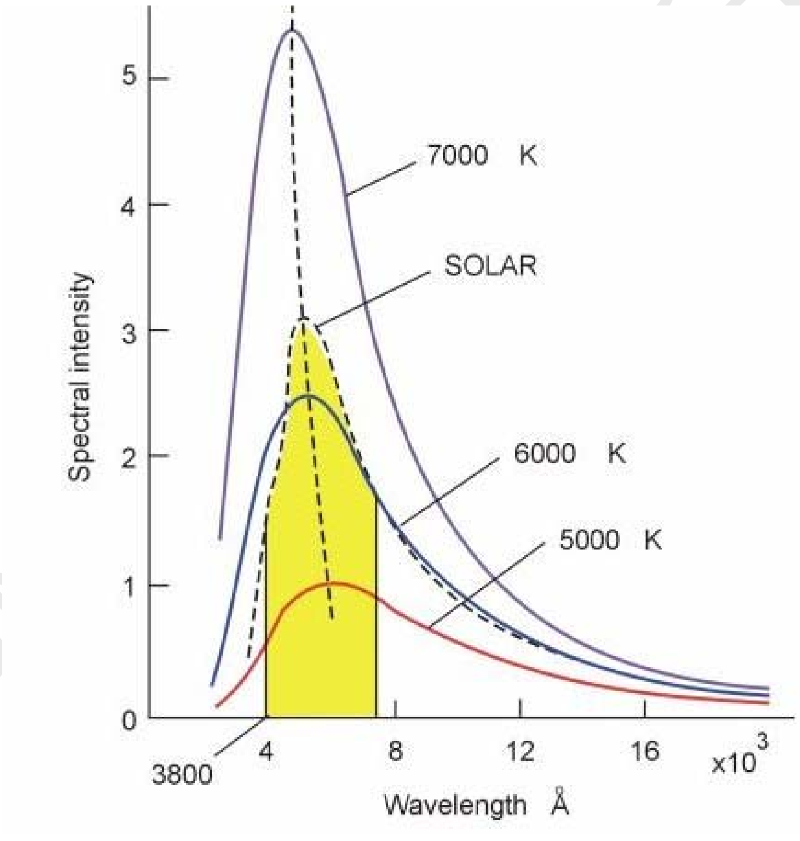

Figure 1. Blackbody energy distribution curves. The sun's spectral curve is presented by the shaded curve and is in the range of visible wavelengths.

3.4. Blackbody Absorbers - Application to Desalination

Solar radiation is absorbed in various ratios by physical materials, depending on their special radiation or emittance properties, the perfect absorber being always the blackbody. By using black material in flat-plate collectors and solar stills, the maximum absorbance of the incident radiation can be reached. The energy E_b emitted by a perfect blackbody is calculated for all wave lengths λ and for a temperature T_b K from the Stefan-Bolzmann equation derived from the integration of Planck's law:

$$E_b = E_b\lambda\ \mathrm{d}\lambda = \sigma \mathrm{T}_\mathrm{b}^4 = 5.6697\times10^{-8} T_b^4\ \ \mathrm{W\,m^{-2}} \qquad (5)$$

For solar distillation and flat-plate collectors efficient sky radiation is an important factor. Sky radiation refers to the radiation exchange between sky and a surface, *p*, under observation, A_p m^2, of temperature T_p K. The sky is considered as a blackbody of temperature, T_s. Considering the blackbody perfect absorbance, α, or emittance, ε, as 1.0, all natural materials may have an absorbance or emittance, α, or, ε < 1.0. According to the above Stefan-Bolzmann equation for an emittance, ε, of a collector or solar still of absorbance surface *A* m^2, the net mutual radiation is given as:

$$Q = \varepsilon\times A_p\times\sigma\times(T_b^4 - T_s^4) = \varepsilon\times A_p\times 5.6697\times10^{-8}(T_p^4 - T_s^4)\ \mathrm{J\,s^{-1}} \qquad (6)$$

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Bibliography and Suggestions for further study

A. Wokaun. Beyond Kyoto: The risks and how to cope. UN Framework Convention on Climate Change. Bonn, Germany, 16-25 June 2004

Akasaka H and Kuroki S (1991) Models of circumsolar radiation and diffuse sky radiation including cloudy sky (Proceedings Biennial Congress of International Solar Energy Society (ISES), Denver, CO, 19-23 August, 1991), 1, Part II, 933-938.

Al-Karaghouli A.A., Alnaser W.E. (2004), *Experimental comparative study of the performance of single and double basin solar-stills*. Appl Energy **77**(**3**), pp. 317-25.

Al-Karaghouli A.A., Alnaser W.E. (2004), *Performances of single and double basin solar-stills.* Solar Energy **78**(**3**), pp. 347-54.

Al-Shammiri M., Safar M(1999). Multi-effect distillation plants: state of the art. Desalination , 126:45-59.

Atwater M A and Ball J T (1978) A numerical radiation model based on standard meteorological observations. *Solar Energy* 21, 163-170.

Bendt P M, Collares-Pereira M and Rabl A (1981) The frequency distribution of daily insolation values. *Solar Energy* 27(1), 1-5.

Benford F and Bock J E (1939) A time analysis of sunshine. *Transaction of the American Illumination Engineering Society* 34, 200-204.

Berdahl P and Martin M (1984) Emissivity of clear skies. *Solar Energy* 32, 663-664.

Boes E C (1980) Fundamentals of solar radiation. *Solar Energy Handbook* (Ed. J F Kreith, F Kreith), New York: McGraw Hill.

Chafik, E., 2003. A new type of seawater desalination plants using solar energy. Desalination

Collares-Pereira M and Raml A (1979) The hourly daily insolation values. *Solar Energy* 22, 155-164.

Cooper I (1969) The absorption of solar radiation in solar stills. *Solar Energy* 12, 313-331; 333-346.

Corrado Sommariva ,(2010),COURSES IN DESALINATION, Thermal Desalination

Delyannis E. (2003), *Historic background of desalination and renewable energies.* Solar Energy **75**(**5**), Elsevier pp. 357-66.

Diabete L G, Moussu G and Wald L (1989) Description of an operational tool for determining global solar radiation at ground using geostationary satellite images. *Solar Energy* 42, 201-207.

Dickinson W C and Cheremisinoff P N (1980) *Solar Energy Technology Handbook,* Part A, *Engineering Fundamentals.* 881 pp., New York: Marchel Dekker - Butterworths.

Duffie J A and Beckman W A (1991) *Solar Engineering of Thermal Processes*, 919 pp. New York: John Wiley and Sons.

Erbs D G, Klein S A and Duffie J A (1982) Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy* 28, 293-302.

Faiman D, Feuermann P et al. (1991) Use of a multipyranometer instrument for obtaining the irradiance on inclined planes (Proceedings Biennial Congress of International Solar Energy Society (ISES), Denver, CO, 19-23 August 1991), 1, Part II.

Florides G., Kalogirou S. (2004), *Ground heat exchangers – a review.* Proceedings of third international conference on heat power cycles, Larnaca, Cyprus, on CD-ROM.

García-Rodríguez L. (2003), “Renewable energy applications in desalination: state of the art”, Solar Energy 75, 381-393.

García-Rodríguez, L., 2002, Seawater desalination driven by renewable energies: a review. Desalination 143: 103-113

Gregorzewski, A. and Genthner, K., High efficiency seawater distillation with heat recovery by absorption heat pumps. Proceedings of the IDA World Congress on Desalination and Water Reuse, pp. 97-113, Abu Dhabi, November 18-24, 1995.

Harrison L (1991) Multi-spectral Automated rotating shadow band radiometry in the atmospheric radiation measurements (ARM) program. (Proceedings Biennial Congress of International Solar Energy Society (ISES), Denver CO, 19-23 August 1991), 1, Part II, 893-804.

Hay E (1979) Calculation of the monthly mean solar radiation for horizontal and inclined surfaces. *Solar Energy* 23, 301-307.

Hottel C (1976) A simple model for estimating the transmittance of direct solar radiation through clear atmospheres. *Solar Energy* 18, 129-134.

Hunn B D and Calafell D O (1977) Determination of average ground reflectivity for solar collectors. *Solar Energy* 19, 87-89.

Hunt A J, Grether D F and Wahlig M (1977) Techniques for measuring circumsolar radiation. Lawrence Berkeley Laboratory, 30 pp. Report No LBL-8345.

Iqbal M (1983) *An Introduction to Solar Radiation*. Toronto Canada: Academic Press.

ISES, International Solar Energy Society (1978) *Units and Symbols in Solar Energy* (ed. W A Beckman et al.). *Solar Energy* 21, 61-68, *Solar Energy*, 57, XVII-XVIII, 1996.

Jeter S M and Balaras C A (1990) Development of improved solar radiation models for predicting beam transmittance. *Solar Energy* 44, 149-156.

Jurado M, Caridad J M and Ruiz V (1995) Statistical distribution of the clearness index with radiation data integrated over five minutes. *Solar Energy* 55, 469-473.

Kalogirou S. (2003), *The potential of solar industrial process heat applications.* Appl Energy, **76**(**4**), pp. 337-61.Lysen E. (2003), *An outlook for the 21st century.* Renew Energy World, **6**(**1**), pp. 43-53.

Kalogirou S. (2004), *Solar energy collectors and applications.* Prog Energy Combust Sci, **30**(**3**), pp. 231-95

Karameldin, A. Lotfy and S. Mekhemar (2003), *The Red Sea area wind-driven mechanical vapor compression desalination system,* Desalination **153**, Elsevier pp. 47-53.

Kudish A.I., Evseev E.G., Walter G., Priebe T. (2003),*Simulation study on a solar desalination system utilizing an evaporator/condenser chamber*. Energy Convers Manage **44**(**10**), Elsevier, pp. 1653-70.

Lamm L O (1981) A new analytical expression for equation of time. *Solar Energy* 26, 465-469.

Lee B III, Barstrom B R, Luther M R, Cess R D (1986) Solar irradiance measurements using the earth radiation budget experiment solar monitors (6th Conference on Atmospheric Radiation, Boston, 1986), Paper J5-J8.

Liu B Y H and Jordan R C (1960) The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy* 4, 1-19.

Liu B Y H and Jordan R C (1963) A rational procedure for predicting the long term average performance of flat-plate collectors. *Solar Energy* 17, 53 -60.

Lof G O, Duffie J A and Smith C O (1966) *World Distribution of Solar Radiation*. Solar Laboratory, The University of Wisconsin, Engineering Experimental Station, Rep. 21, 59 pp.

M.A. Darwish , Iain McGregor, (2005), *Five days' Intensive Course on - Thermal Desalination Processes Fundamentals and Practice,* MEDRC & Water Research Center Sultan Qaboos University, Oman

Mangal B S (1990) *Solar Power Engineering*, 474 pp., McGraw Hill: New Delhi, Tata.

Maxwell E L et al. (1991) *Producing a National Solar Radiation Data Base.* (Proceedings of the Biennial Congress of ISES, Denver Colorado, 19-23 August 1991) 1, Part II, 1138, pp. 1007-1012. Oxford: Pergamon Press.

Millow B. and Zarza E., Advanced MED solar desalination plants. Configurations, costs, future – Seven years of experience at the Plataforma Solar de Almería (Spain), Desalination 108, pp. 51-58, 1996.

Müller-Holst, H., 2007. Solar Thermal Desalination using the Multiple Effec Humidification (MEH) method, Book Chapter, Solar Desalination for the 21st Century, 215–225.

NASA (1971) *Solar Electromagnetic Radiation,* NASA Report SP-8005.

Parekh S., Farid M.M., Selman R.R., Al-Hallaj S. (2003), *Solar desalination with humidification-dehumidification technique – a comprehensive technical review*. Desalination **160**, Elsevier pp. 167-86.

Perez R K et al. (1987) Variations of the luminous efficiency of global and diffuse radiation and zenith luminance with weather conditions: description of a potential method to generate key daylight availability data from existing solar radiation bases. *Solar Energy* 38, 33-44.

Perez R R, Zelenka A and Inechen P (1990) Climatic evaluation of models that predict hourly direct irradiance from hourly global irradiance. Prospects for performance Improvements. *Solar Energy* 44, 99-108.

Perez R, et al. (1991) Dynamic model for hourly global to-direct irradiance conversion. (Proceedings Biennial Congress of the International Solar Energy Society (ISES), Denver, CO, 19-23 August 1991), 1, Part II, 951-956.

Rabl A (1981) Yearly average performance of the principal solar collector types, *Solar Energy* 27, 215-233.

Randall C M and Bird R (1989) *Insolation Models and Algorithms*, Chapter 3: *Solar Resources*, (Ed. R L Hulstrom), pp. 141-150, Cambridge, MA: MIT Press.

Reindl D T, Beckman W A and Duffie J A (1990) Evaluation of hourly tilted surface radiation models. *Solar Energy* 45, 9-17.

Reindle T D, Beckman W A and Duffie J A (1990) Diffuse fraction correlations. *Solar Energy* 45, 1-7.

Riordan C (1992) Solar radiation resource assessment. *Advances in Solar Energy* (Ed. K W Böer) 7, 211-238.

Robinson N (1966) *Solar Radiation*, 347 pp. Amsterdam: Elsevier Publ. Comp.

Sandia National Laboratories (1990) *Handbook of Recommended Design Practices*. Rep. SAND87-7023.

Sayig A.A.M. (2004), *The reality of renewable energy*. Renewable Energy, pp. 10-15.

Sayigh A A M (1984) *Solar radiation fundamentals* (Proceedings 3rd International Symposium on "Non Conventional Energy Sources"), ACIF Series, Vol. 3. (Eds Furlan G, Rodrigez H, Violini G) pp. 352-395, Singapore: World Scientific Publ. Co., Pte Ltd.

Schulze-Kegel D and Heidt F D (1996) Mapping of global radiation with meteosat. *Solar Energy* 58, 77-90.

SERI (1982) Direct normal solar radiation data manual, Golden, Colorado, USA, Rep. SERI SP-281-1658.

SERI (Solar Energy Research Institute) (1981) Solar radiation energy resource Atlas of the United States, Golden, Colorado, USA, Rep. SERI SP-642-1037.

Sharma V B and Mullick S C (1993) Calculation of hourly output of a solar collector, *Transaction ASME, Journal Solar Energy Engineering* 115, 231-236.

Soteris A. Kalogirou (2005), *Seawater desalination using renewable energy sources*, Progress in Energy and Combustion Science **31**, Elsevier, pp. 242-281.

Stewart R, Spenser D W and Perez R (1985) The Measurement of solar radiation, *Advances in Solar Energy*, Vol. 2, (ed. K W Boer and J A Duffie), pp. 1-49, New York: Plenum Press.

Thomson M., Infield D. (2003), *A photovoltaic-powered seawater reverse-osmosis system without batteries*. Desalination **153**(1-3), pp. 1-8

Tiwari G.N., Singh H.N., Tripathi R. (2003), *Present status of solar distillation.* Solar Energy 75(5), Elsevier, pp. 367-73.

Tzen E., Morris R. (2003), *Renewable energy sources for desalination.* Solar Energy **75**(**5**), Elsevier, pp. 375-9.

United Nations, Water for People, Water for Life – UN World Water Development Report, UNESCO Publishing, Paris, 2003.

University of Lowell Photovoltaic Program (1991) *International Solar Irradiation Data Base*, Lowell MA, Rep. No 508-934-3376.

Utrillas M P and Martinez-Lozano J A (1995) The performance evaluation of several versions of the Perez tilted diffuse irradiance model, *Solar Energy* 53, 155-162.

Wiseman, R., Desalination business “stabilised on a high level” – IDA report, Desalination & Water Reuse 14(2), pp. 14-17, 2004.

WOM (World Meteorological Organization) (1980) Report on World Insolation Data.