Applied Energy 190 (2017) 1138–1158

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Statistical analysis for the characterization of solar energy utilization and inter-comparison of solar radiation at two sites in Cyprus

S. Pashiardis [a], S.A. Kalogirou [a,*], A. Pelengaris [b]

[a] Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, P.O. Box 50329, 3603 Limassol, Cyprus
[b] Cyprus Public Works Department, Ministry of Transport Communications and Works, Strovolos Avenue 165, 2048 Strovolos, Cyprus

HIGHLIGHTS

- Statistical analysis of global radiation.
- Monthly and diurnal variation of global radiation.
- Frequency distribution of global radiation.
- Relationship between global and other radiation parameters.
- Comparison of global radiation between two sites.

ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form 5 January 2017
Accepted 11 January 2017
Available online 21 January 2017

Keywords:
Global radiation
Diffuse radiation
Horizontal beam radiation
Statistical analysis
Clearness index
Diffuse ratio
Frequency distribution
Linke turbidity factor

ABSTRACT

A statistical analysis and inter-comparison of the solar radiation at two sites in Cyprus representing two different climate regimes of the island (Athalassa-inland plain vs Larnaca-coastal location) covering the period January 2013–December 2015 is presented. Mean annual and mean monthly daily totals of the global, horizontal beam and diffuse radiation and their frequency distribution at both sites are computed and discussed. The values of skewness and kurtosis coefficients are used to define the frequency distribution type of the above radiation parameters on a monthly basis. The statistical analysis is extended to the daily clearness index (K_T), diffuse ratio (K_D), and the ratio of horizontal beam to global radiation ($K_{B,G}$). Furthermore, the influencing factors on the magnitude of the radiation components were examined. The value of K_T was used to classify three different types of days such as clear, partially cloudy and cloudy days. Then, a statistical analysis of the solar radiation components was performed. On an average annual basis, more than 80% of the days are classified as either clear or partially cloudy at both stations. Additionally, the influence of the atmospheric absorption and scattering of the solar radiation under clear skies was examined on the basis of the Linke turbidity factor (T_L). The results of this analysis are used to characterize and compare the radiation regimes of the two sites. Both sites have relatively high intensity of global and direct horizontal radiation. The annual average daily global radiation intensity is 18.5 MJ m^{-2} at Athalassa and 19.9 MJ m^{-2} at Larnaca. The horizontal beam radiation is 13.1 MJ m^{-2} for Athalassa and 14.2 MJ m^{-2} for Larnaca. Therefore, the fraction of the beam component of the global radiation is comparatively high at both sites, as indicated by the annual average daily fraction which is greater than 0.600. Generally, Larnaca has slightly higher rates of global radiation than Athalassa, as indicated by the average yearly cumulative global irradiation which is 6763 MJ m^{-2} for Athalassa and 7274 MJ m^{-2} for Larnaca.

1. Introduction

The knowledge of the solar radiation reaching the ground surface is important for sizing and optimizing the performances of solar collectors and photovoltaic systems. Therefore, it is necessary to know global, diffuse and beam radiation intensities, as well as their frequency distribution. The most frequent solar elements which are measured in most meteorological stations are the global solar radiation on horizontal surface and the sunshine duration. Global radiation can be easily estimated from sunshine duration data using the Ångstrom formula. The knowledge of global radiation is sufficient for the flat thermal collectors. However, some of the systems, such as concentrating systems, require information

* Corresponding author.
E-mail address: soteris.kalogirou@cut.ac.cy (S.A. Kalogirou).

http://dx.doi.org/10.1016/j.apenergy.2017.01.018
0306-2619/

Nomenclature

A_s	skewness coefficient
B	direct beam horizontal irradiance ($B = B_n * \cos\theta_z = B_n \sin\alpha_s$) (W m^{-2})
B_c	direct beam horizontal irradiance for clear sky conditions (W m^{-2})
B_{nc}	direct beam normal irradiance for clear sky conditions (W m^{-2})
B_d	daily direct beam horizontal irradiation (MJ m^{-2})
B_{nd}	daily direct beam normal irradiation (MJ m^{-2})
CV	coefficient of variation (%)
D_d	daily diffuse horizontal irradiation (MJ m^{-2})
G_{0d}	daily extraterrestrial irradiation (ETR) (MJ m^{-2})
G_d	daily global irradiation (MJ m^{-2})
G_{sc}	solar constant (1367 W m^{-2})
j	Julian day number (1–365)
j'	day angle (°)
K	kurtosis
K_B	daily beam clearness index ($K_B = B_d/G_{0d}$)
$K_{B,G}$	daily ratio of horizontal beam to global radiation, $K_{B,G} = B_d/G_d$
K_D	daily diffuse ratio ($K_D = D_d/G_d$)
$K_{D,B}$	daily ratio of diffuse to horizontal beam radiation, $K_{D,B} = D_d/B_d$
K_T	daily clearness index ($K_T = G_d/G_{0d}$)
m	relative optical air mass
N	nonmissing observations
N^*	missing observations
PAR	photosynthetic active radiation (MJ m^{-2})
P	pressure at the station level (h Pa)
P_0	standard atmospheric pressure (P_0 = 1013.25 h Pa)
Q1	first quartile
Q3	third quartile
R_d	reflected daily irradiation (MJ m^{-2})
R_{nsd}	daily Net shortwave irradiation (MJ m^{-2})
S_{0d}	astronomical day length (h)
S_d	daily sunshine duration (h)
T_L	Linke turbidity factor
z	site elevation (m)

Greek

α_s	solar elevation angle (°)
δ_R	Rayleigh optical thickness
ε	earth-sun distance correction
θ_z	solar zenith angle (°)
ρ	daily Albedo (R_d/G_d)
σ	daily relative sunshine ($\sigma = S_d/S_{0d}$)
φ	latitude (°)

on the direct beam component, whereas in the case of tilted-plane surfaces, the diffuse component of the solar radiation is also important for the compilation of system performance.

The direct component is measured using a pyrheliometer installed on a solar tracking system which is very expensive device. The diffuse component can be measured using a pyranometer equipped with a solar shadow band. Then, the direct component can be estimated from the difference of global and diffuse radiation both measured on horizontal surface. A number of empirical and physical models can be also used to estimate the said solar components. It is also necessary to be able to design solar energy conversion systems so as to operate as close as possible and at the maximum possible duration, to full capacity. It is also of interest to identify the limits within which the quantity of solar radiation can vary during different months of the year and additionally the possibility of occurrence of a number of consecutive days with values smaller or larger than specified limits of global solar radiation.

The first attempt for the assessment of the solar radiation climate of Cyprus was presented by Jacovides et al. [1] in 1993. During the last twenty years, Jacovides et al. [2–8] have calculated the various components of solar radiation using empirical models. Kambezides [9] presented the 'Typical Meteorological Year' for Nicosia. More recently, Kalogirou et al. [10] presented a statistical analysis and inter-comparison of the solar global radiation between an inland and coastal location in Cyprus using measurements of 21 months at both sites. Mean annual, monthly and daily totals, diurnal variation and frequency distribution of daily totals at both sites were computed and discussed. The same type of statistical analysis was extended to the clearness index and sunshine duration. The two sites enjoy high global and horizontal beam radiation intensities. The common feature of all the above studies is that they rely mostly on measurements of solar radiation carried out in the actinometric stations of Athalassa and Larnaca.

The purpose of the present study is to implement the methodology proposed by Ianetz et al. [11], for characterization and inter-comparison of the two sites in Cyprus with respect to the global, beam and diffuse radiation intensities by expanding the period of measurements to three years and calculating the frequency distribution on a monthly basis for each radiation component. The analysis of the frequency distribution and distribution type of a particular solar irradiation component are very important parameters in the design of solar irradiation conversion systems [10]. According to the methodology introduced by Ianetz and Kudish [12] the characteristics of the frequency distributions of the various solar radiation parameters are determined from the values of skewness (*As*) and kurtosis (*K*) coefficients. These statistical parameters describe the breath of the distribution curve, its degree of asymmetry and its shape relative to that for a normal distribution curve. The frequency distribution types as a function of the skewness and kurtosis values are defined in Table 1. In practise, the distribution types can be extended to estimate the cumulative frequency curves of each radiation component which give information on the probability that daily values are exciting certain thresholds of solar radiation in different months of the year.

Table 1
Definition of the types of frequency distribution according to the range of the skewness and kurtosis values as suggested by Ianetz and Kudish [12].

Distribution type no.	Distribution curve	Skewness (As)	Kurtosis (K)
I	Normal	$-0.4 < As < 0.4$	$-0.8 < K < 0.8$
II	Almost normal with positive tail	$As \geqslant 0.4$	$-0.8 < K < 0.8$
III	Narrow peak with positive tail	$As \geqslant 0.4$	$K \leqslant -0.8$ $K \geqslant 0.8$
IV	Almost normal with negative tail	$As \leqslant -0.4$	$-0.8 < K < 0.8$
V	Narrow peak with negative tail	$As \leqslant -0.4$	$K \geqslant 0.8$
VI	Bimodal, symmetrical with flat peak	$-0.4 < As < 0.4$	$K \leqslant -0.8$