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ScienceDirect

Solar Energy 132 (2016) 430–441

SOLAR ENERGY

www.elsevier.com/locate/solener

Solar resource assessment in Seville, Spain. Statistical characterisation of solar radiation at different time resolutions

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Received 30 July 2015; received in revised form 14 March 2016; accepted 17 March 2016
Available online 4 April 2016

Communicated by: Associate Editor Frank Vignola

Abstract

The characterisation of the solar resource of a site is essential for different phases of solar energy projects. While only rough estimates of yearly levels of solar irradiation (global or direct, depending on the technology) are needed in their very early stages, the required depth of the assessment increases as the project advances, including long-term estimates that can only be obtained through a statistical analysis of a continuous and long-term database of solar radiation measurements. This paper provides the results of a statistical analysis of thirteen years of Global Horizontal Insolation (GHI) measurements and Direct Normal Insolation (DNI) measurements from Seville, Spain (37.4°N, 6.05°W) at different time resolutions, i.e. from annual to nearly instantaneous (5-s). In addition, a new methodology for gap-filling is proposed which keeps the frequency distribution of the original dataset and reduces the uncertainty of the aggregated values (hourly, daily, monthly, yearly) due to the gaps. Some relevant results of this analysis are: (a) the instantaneous values of GHI and DNI have bimodal distributions, although of different characteristics, in agreement with the results of some works developed in similar climate locations; (b) the frequency distributions of the instantaneous and 10-min clearness index (k_t) and beam fraction index (k_b) are almost identical, suggesting 10 min as a good time resolution for the simulation of Concentrated Solar Power (CSP) systems oriented to feasibility analyses; (c) the distributions of hourly k_t and k_b values, show significant differences with respect to the instantaneous ones; (d) the difference between the percentile 99 (P99) of the instantaneous GHI and its maximum value is very high, because of the enhancement effect due to the cloud reflection, while for the DNI the corresponding values are much closer. The comparison with the results of other locations of similar climates suggest that these results can be extrapolated, at least, to other locations of similar climates. Other, more site-specific, results are: (a) the number of typical overcast days in summer is extremely low, while it takes its maximum value in December, suggesting this month as the best for maintenance operations that require halting the operation of CSP plants; (b) the annual mean daily values are 4.98 $kW\,h\,m^{-2}$ for GHI and 5.68 $kW\,h\,m^{-2}$ for DNI, with a low inter-annual variability and a greater monthly variability which depends on the season. The monthly and yearly average values from Seville have been compared with three long-term databases derived from satellite images. The best concordance in GHI values is found with NASA's Surface Meteorology and Solar Energy (NASA SSE), but NASA SSE provides significantly higher DNI values compared to the Seville database. A comparison of one year of DNI and GHI measurements recorded at two locations, Durban (South Africa) and Abu Dhabi (United Arab Emirates), with high solar potential is also addressed.

Keywords: Solar resource assessment; GHI; DNI; Clearness index

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http://dx.doi.org/10.1016/j.solener.2016.03.032
0038-092X/

Nomenclature

k_t	clearness index	I_{g0}	horizontal global irradiance
$k^{\Delta t}_t$	clearness index of the aggregation time interval Δt	I_o	horizontal extraterrestrial irradiance
k^d_t	daily clearness index	I_{cs}	solar constant
$k^{\Delta t}_b$	beam fraction index of the aggregation time interval Δt	ε_0	Sun-Earth distance correction factor
k_b	beam fraction index	θ_z	solar zenith angle
		I_{bn}	normal direct irradiance
		I_n	normal extraterrestrial irradiance

1. Introduction

Characterising the solar resource of a site is essential for different phases of solar energy projects. While only rough estimates of yearly levels of solar irradiation (global or direct, depending on the technology) are needed in their very early stages, the required depth of the assessment increases as the project advances, including long-term estimates that can only be obtained through a statistical analysis. The statistical characterisation of the resource requires long-term series of solar radiation measurements –between 6 and 30 years, depending on the researcher (Meyer, 2010; Stoffel et al., 2010)– with different requirements in terms of time resolution depending on the specific use or application of the measurements. The time resolution of the solar radiation data used for simulations may have a significant effect on the results of feasibility analyses, depending on the dynamics of the solar energy system under consideration (Hirsch and Schenk, 2010). In the case of CSP plants, where the most relevant variable is the DNI, some authors (Cebecauer & Suri, 2015) suggest that the use of 10-min averaged values is an appropriate choice for simulation oriented to feasibility analyses. High-resolution instantaneous data are required for the detailed analysis of transient processes associated to cloud passages and certain operational procedures, like plant start-up and shut-down.

Availability of ground-measured DNI databases with long and continuous time coverage is scarce. Thus, it is a common practice to derive DNI values from GHI measurements or satellite-based estimates, which are more frequently available. The synthetic generation of DNI series from GHI should take into account the differences with regards to the statistical distribution of these variables in different time intervals (Boland et al., 2013; Dugaria et al., 2015).

Different researchers have studied the statistical characteristics of the solar radiation in different time intervals. Early studies were focused on the analysis of daily values mainly. The most relevant work was that by Liu and Jordan (1960). Some other relevant studies analysed and/or compared the distributions of hourly and instantaneous values (Jurado et al., 1995; Olseth and Skartveit, 1989; Skartveit and Olseth, 1992; Suehrcke and McCormick, 1988). Complete literature reviews about the statistical characteristics of the solar radiation components in monthly, daily, hourly and instantaneous resolution have been published by Tovar-Pescador (2008) and Fernández-Peruchena and Bernardos (2015). In the last years, the analysis of the instantaneous behaviour of solar radiation attracts special attention in the context of solar radiation component modelling for simulation of solar systems (Bright et al., 2015; Morf, 2013; Ngoko et al., 2014). On the other hand, the analysis of monthly and annual solar radiation values is addressed for quantifying and qualifying the solar resource at a location. Examples of such studies that analyse regions with promising solar potential are presented in (Bachour and Perez-Astudillo, 2014; Islam et al., 2010, 2009; Zawilska and Brooks, 2011). Many of these studies are based on data collected over relatively short periods (less than 5 years).

Solar energy performance simulations need continuous time-series of radiation data. It is very common to find gaps, wrong time-stamps or improperly measured data in a long solar radiation database (Kumar et al., 2013). Designing and applying a good gap filling procedure is not an easy task. A common procedure to estimate monthly and annual values from time series with gaps is to fill the missing days with the average values of the available days of the same month. This procedure may result in inaccurate estimates, depending on the number of missing days. Ogunsola and Song (2014) compares different approaches based on the analysis of time series of solar radiation and other meteorological variables for restoring hourly solar radiation data. Other authors suggest a simple linear interpolation when gaps are up 3 h and filling gap with neighbouring data or data of the same day from other years when the gaps are greater. The use of the solar radiation components or data from a nearby station is considered the best option (Hoyer-Klick et al., 2009; Schwandt et al., 2014).

In this work, a novel procedure for gap-filling, which keeps the frequency distribution of the original dataset is proposed. This procedure has been applied to 13 years of DNI and GHI measurements from the radiometric station of the Group of Thermodynamics and Renewable Energies (GTER) of the University of Seville (Spain).

An analysis of the solar resource in Seville based on this database is presented. The processed database is