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A statistical characterization of the long-term solar resource: Towards risk assessment for solar power projects

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Abstract

In this study, a statistical characterization of annual solar irradiation series is presented which can be used as input in risk assessment for securing competitive financing for solar power projects. To perform this task, an analysis of annual Direct Normal solar Irradiation (DNI) and Global Horizontal solar Irradiation (GHI) probability density functions has been carried out, showing that annual DNI and GHI distributions are described by Weibull and normal functions, respectively. Normal fitting of annual GHI distributions yields uncertainties in mean parameter below 1%, and uncertainties in standard deviation parameter of ~12%. Weibull fitting of annual DNI distributions yields uncertainties in scale parameter of ~1%, and uncertainties in shape parameter of ~15%. For each location analyzed in this study, the estimated regression coefficients (and their uncertainties) of annual solar irradiation distributions fitting are used to obtain percentile values and their respective associated uncertainties. The greatest uncertainties are associated with the lower percentiles, being 1st percentile uncertainty ~1.6% and ~4% for GHI and DNI respectively. Finally, according to the results obtained in this work, a minimum of 11 years of GHI and 15 years of DNI are recommended for their statistical characterization.

Keywords: Solar resource; Percentile; Meteorological variability; Risk analysis

1. Introduction

The variability of the solar resource plays a significant role in estimating the probability of future energy yield of a solar power plant, and its influence the financial conditions that the project is likely to receive (Fernández-Peruchena and Bernardos, 2015; Ho and Kolb, 2010; Lohmann et al., 2006). Consequently, solar-power financing is usually based on a statistical assessment of the solar resource. In particular, *worst cases* of solar resource availability are often analyzed in order to ensure the viability of the project. These

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worst cases are often characterized by annual solar radiation datasets with high probability of exceedance of their annual values. As an example, Fitch Rating recommends to evaluate the probability of exceedance scenarios of 50%, 90% and 99% (FitchRatings, 2011). Probability of exceedance scenarios are not to be confused with percentiles, both indicators provide complementary information: a percentile 10 will be exceeded with a probability of 90%.

Unfortunately, there is at present no scientific consensus or industry-standard methodology for performing risk assessment in solar power projects (Kleissl, 2013), but in recent times research efforts are being targeted to deal with the solar resource variability analysis in the feasibility assessment of a solar power plant. At least, a 10-year database is recommended to statistically characterize the solar resource in a location, although more years would help to reduce the uncertainty related to the high inter-annual variability of the annual solar irradiation (Gueymard and Wilcox, 2009; Meyer, 2010; Vignola, 2013). In this sense, historical solar radiation datasets are key elements in designing solar power systems, and also critical in their performance risk analysis. When the period covered by the database is assumed to be sufficiently representative, no particular statistical probability distribution is assumed to fit the data, and rather an empirical cumulative distribution function (ECDF) of the data is used to calculate the percentile values (Dobos et al., 2012). Unfortunately, these datasets are generally not available near the design site. To overcome this difficulty, recent research is oriented to the development of methods to expand the datasets extracting information from the available database (Bohlen and Schumacher, 1996; Fernández-Peruchena et al., 2014a, 2014b, 2015b; Röttinger et al., 2015; Vignola, 2013). Similarly, recent works propose the creation of hybrid sets of modeled or generated solar irradiance data enhanced by superimposed short term fluctuations (Beyer et al., 2010; Fernández-Peruchena et al., 2015a; Fernández-Peruchena and Gastón, 2016; Schenk and Hirsch, 2010; Wey et al., 2012). Another strategy in the statistical characterization of solar irradiation consists in assuming a type of distribution function for the dataset; e.g.: the SolarGIS method (Cebecauer and Suri, 2015) considers the combined uncertainty of the estimate and interannual variability as the unbiased standard deviation of a normal distribution of annual solar irradiation values to estimate the different exceedance scenarios.

This scenario has led to the creation of a panel of experts in AENOR (Spanish Association for Standardization and Certification), which is analyzing methodologies to statistically describe annual solar Irradiation variability. The preliminary results obtained in accordance with such works are presented in this paper.

The goal of this contribution is to present a simple and robust methodology for evaluating the statistical properties of annual Direct Normal solar Irradiation (DNI) and Global Horizontal solar Irradiation (GHI) series. The paper is presented as follows: Section 2 provides a theoretical background in percentile and distribution functions (normal and Weibull). Section 3 describes measured data used in the work, as well as the analysis carried out. Section 4 shows the results found and in Section 5 discussion, conclusions and future work are drawn.

2. Theoretical background

2.1. Background in percentile

Given a real-valued random variable X with a strictly increasing and continuous cumulative distribution function F, then $F^{-1}(p)$, $p \in [0, 1]$ is the unique real number x such that $F(x) = p$, which defines the quantile function Q (Eq. (1)):

$$Q(p) = F^{-1}(p) \tag{1}$$

The kth n-tile P_k is that value of x, say x_k, which corresponds to a cumulative frequency of $N \cdot k/n$. If $n = 4$, the quantity is called a quartile, and if $n = 100$, it is called a percentile.

The definition of quantile functions for discrete rather than continuous distributions requires a bit more work since the discrete nature of such a distribution means that there may be gaps between values in the domain of the distribution function and/or "plateaus" in its range. Moreover, there are a wide variety of methodologies for estimating percentile values for discrete distributions providing different percentile values for the same set of data (as nearest rank or linear interpolation between closest ranks methods). Most of these methods assign a probability of 0 to the lower value of the dataset, and a probability of 1 to the higher one, and consequently do not provide more extreme values than those available in the dataset. Notwithstanding, when establishing a variability range in annual solar irradiation, it is of outmost importance to make a statement about typical values in a population larger than those available in the study (as typically this population will be lower than the expected lifetime of a solar power plant). Consequently, in this work, we calculate the percentile values of annual solar irradiation series by employing continuous probability density functions.

Finally, it is worth to remark that, mathematically, a percentile is a value at or below which a given percentage or fraction of the variable values lie. It is also important to bear in mind the *exceedance probability*, which is the probability that a certain value will be exceeded. The exceedance probability, used also in solar resource assessment (Dobos et al., 2012), is the complementary concept of percentile.

2.2. Background in normal and Weibull functions

The normal (or Gaussian) is the most commonly used distribution to model univariate data from a population or from an experiment. The Central Limit Theorem suggests that when the underlying variables are random,