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Probabilistic assessment of concentrated solar power plants yield: The EVA methodology

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ABSTRACT

Understanding the long-term temporal variability of solar resource is fundamental in any assessment of solar energy potential. The variability of the solar resource (as shown by historical solar data) plays a significant role in the statistical description of the future performance of a solar power plant, thus influencing its financing conditions. In particular, solar-power financing is mainly based on a statistical quantification of the solar resource. In this work, a methodology for generating meteorological years representative of a given annual probability of exceedance of solar irradiation is presented, which can be used as input in risk assessment for securing competitive financing for Concentrating Solar Thermal Power (CSTP) projects. This methodology, which has been named EVA, is based on the variability and seasonality of monthly Direct Normal solar Irradiation (DNI) values and uses as boundary condition the annual DNI value representative for a given probability of exceedance. The results are validated against a 34-year series of net energy yield calculated at hourly intervals from measured solar irradiance data and meteorological, and they are also supplemented with the analysis of uncertainty associated to the probabilities of exceedance estimates. Relations between DNI and CSTP energy yields at different time scales are also analyzed and discussed.

1. Introduction

The adoption of renewable energy technologies aimed at developing a sustainable electricity generation system is essential for avoiding or mitigating impacts on regional climatic conditions, environmental degradation, reserves of fuel resources and for securing the energy supply in the future [1]. In this scenario, Concentrating Solar Thermal Power (CSTP) is expected to be one of the leading renewable energy technologies with about 980 GW of newly installed capacity by 2050 [2]. The significant experience acquired during the last years suggests that CSTP projects will have stable energy production and operating costs consistent with expectations, and also capital costs will decline significantly as the sector reaches maturity resulting in price efficiencies.

CSTP systems collect and concentrate naturally available solar energy in a large land onto a small area using mirrors or lenses. In particular, the beam component of the solar irradiance (Direct Normal solar Irradiance, DNI) is exploited in such facilities as the primary source of energy because of its directional nature. The concentrated solar radiation is used to generate electric power through its conversion into thermal energy, which can be stored, by means of a thermodynamic cycle. Thus, a precise knowledge of the incoming DNI is required for an accurate design and optimization of CSTP plants using energy yield simulation computer programs requiring weather data input. This knowledge, more than just the average DNI available at the proposed site, comprises a deep understanding of the availability and dynamics of the solar resource over different temporal scales (intraday, day, month, year) during the duration of the project life, especially for projects with off-take agreements where there is a time-of-day pricing

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component [3]. In particular, institutions providing finance for CSTP projects require the supply of third-party solar resource assessment. As an example, Fitch Ratings [4] demands to address three major issues:

- Quality of the data used to determine the characteristics of the solar resource.
- Long-term estimate of the average electric energy output from the CSTP project based on the solar resource evaluation and the design of the project.
- Several statistical *probability of exceedance* scenarios of the expected electric energy output.

This paper addresses the third requirement: probability of exceedance scenarios, which are used to estimate the electric generation output under the corresponding scenario. The probability of exceedance value is the electricity generation that the solar resource consultant expects to be exceeded in any given year over the life of the debt with a given probability. This approach provides a theoretical floor output level. For example, according to Fitch Ratings [4], a solar resource assessment should provide the following outputs for probability of exceedance scenarios:

- Probability of exceedance of 50% (P50).
  - o Solar resource consultant's best estimate of the average annual electric yield achievable by the project during its lifetime.
  - o Used to formulate a base case of electric output for a solar plant.

- Probability of exceedance of 90% (P90).
  - o The output that has a 90% probability of being exceeded in any given year over the life of the debt.
  - o Used in rating case determination for the debt issue.
- Probability of exceedance of 99% (P99).
  - o The output that has a 99% probability of being exceeded in any given year over the life of the debt. On a practical level, it represents the lowest output profile, and therefore, the most conservative.
  - o Used as a sensitivity case for rating a solar project.

When the period covered by the available DNI database is assumed to be sufficiently representative, its long-term temporal variability can be characterized by the empirical cumulative distribution function (ECDF) [5]. The meteorological community has deemed that a 30-year interval is sufficient to reflect longer-term climatic trends, based on the recommendations of the International Meteorological Conference in Warsaw in 1933. This period is sufficiently long to filter out many of the short-term inter-annual fluctuations and anomalies. Unfortunately, surface-based measurements of DNI are available only on a relatively sparse network, given the costs of equipment acquisition, operation and management, and therefore 30-years' series are generally not available near the CSTP facility design site [6]. Also, other reliable sources of DNI information (mainly satellite remote-sensing methods and meteorological model outputs) neither provide such period. Consequently, recent research is devoted to the development of methods for extrapolating long-term DNI statistical information from available information at the site [5,7–10]. Unfortunately, current practices for risk evaluation of CSTP plants have significant weaknesses, as they do not allow the analysis of the effects of inter-annual solar irradiation variations on cash flows, and in general they tend to underestimate yields compared to probabilistic modelling [11]. For example, a recent method proposed for the probabilistic modelling of CSTP yield [9] takes into account the uncertainty arising from the plant technical parameters, and characterizes the effect of DNI through its inter-annual variability (which does not cover uncertainties of deriving the DNI long-term average).

They are worth to mention other meteorological parameters (ambient temperature, wind speed and relative humidity, etc.) affecting the CSTP plants yield, which (among other aspects) determine the influence of cooling technology. Notwithstanding, their influence on the energy yield is minor at sites where no extreme weather conditions are prevalent.[1]

In the search of an industry-standard methodology for performing risk assessment for securing competitive financing in CSTP projects, a Panel of Experts was established in 2014 under the auspices of the Spanish Association for Standardization and Certification (AENOR). This Panel of Experts has recommended in the standard UNE 206013:2017 a procedure for generating a meteorological year representative of a given probability of exceedance of annual DNI. This procedure is divided into: 1, the determination of probability of exceedance of annual solar irradiation [7,12]; 2, the assignment of monthly values to reach the annual value of the given probability of exceedance [13]. The procedure was named *EVA*, which stems from the Spanish words "*estacionalidad*" (seasonality) and "*variabilidad*" (variability), referring to the natural processes that inspire it.

In this paper, a 34-year series of CSTP plant yield has been calculated with System Advisor Model (SAM) using hourly ground measurements of solar irradiance and meteorological parameters as inputs. This series has been compared with the CSTP plant yield calculated with meteorological years representative of probability of exceedance generated by means of the EVA methodology. The goal of this contribution is to test the EVA methodology for generating meteorological years representative of the probability of exceedance of solar irradiation at annual scale, and its usefulness in the probabilistic assessment of CSTP plants yield. The rest of the paper is presented as follows: Section 2 describes measured data used in the work, as well as the analysis carried out. Section 3 shows the results and their discussion. Finally, in Section 4, conclusions and future work are drawn.

2. Methods

2.1. Measured data

A 34-year series of hourly solar irradiance and meteorological parameters measured from the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) has been selected for this study. This network has the longest continuous record of DNI measurements in USA. The activity of the SRML started in 1977, with the creation of a five-station global network under the auspices of the Pacific Northwest Regional Commission, motivated by the lack of available and accurate solar radiation data. With 39 stations, this network covers the States of Idaho, Montana, Oregon, Utah, Washington and Wyoming. Table 1 presents details about the location of the station, as well as its radiometric sensors and climatic conditions according to the Köppen-Geiger classification [14].

The Eppley Precision Spectral Pyranometer (PSP) is a World Meteorological Organization (WMO) First Class Radiometer, and the Eppley Normal Incidence Pyrheliometer (NIP) is a WMO First Class Pyrheliometer. The data has been recorded with an hourly interval before 1995, and of 5 min afterwards, and the associated estimated uncertainties for daily irradiances have estimated to be 2% for DNI and 5% for Global Horizontal solar Irradiance (GHI). The radiometers are calibrated on yearly basis with periodic on-site checks with traveling references.

2.2. CSTP plant design and simulation

Over the lifetime of a CSTP plant, the system operates at design conditions only occasionally, with the bulk of operation occurring under part-load conditions depending on solar resource availability. Therefore, a credible economic analysis of these systems requires

[1] For example, the mirrors in a CSTP plant need to be placed in safe mode during strong wind gusts.