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A Methodology for Probabilistic Assessment of Solar Thermal Power Plants Yield

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Abstract. A detailed knowledge of the solar resource is a critical point to perform an economic feasibility analysis of Concentrating Solar Power (CSP) plants. This knowledge must include its magnitude (how much solar energy is available at an area of interest over a long time period), and its variability over time. In particular, DNI inter-annual variations may be large, increasing the return of investment risk in CSP plant projects. This risk is typically evaluated by means of the simulation of the energy delivered by the CSP plant during years with low solar irradiation, which are typically characterized by annual solar radiation datasets with high probability of exceedance of their annual DNI values. In this context, this paper proposes the use meteorological years representative of a given probability of exceedance of annual DNI in order to realistically assess the inter-annual variability of energy yields. The performance of this approach is evaluated in the location of Burns station (University of Oregon Solar Radiation Monitoring Laboratory), where a 34-year (from 1980 to 2013) measured data set of solar irradiance and temperature is available.

INTRODUCTION

Concentrating Solar Power (CSP) technologies collect and concentrate the Direct Normal Irradiance (DNI) incident on the earth's surface, heating a working fluid and afterward producing electricity by means of a thermodynamic cycle. In these technologies, potential projects must be evaluated through simulation prior to its real implementation in order to reduce the financial risk. Thus, these simulations become crucial for performing financial feasibility analysis of commercial projects.

DNI is the most determining variable in the final energy yield of a CSP plant [1, 2], and consequently its detailed assessment is a critical point to perform an economical feasibility analysis of these technologies. DNI exhibits a large geographical and temporal variability due to its great dependence on weather fluctuations and sun position. Knowledge of the solar resource and its variability in both time and space facilitates decision-making processes of the different solar technologies to be deployed in a region, and helps in developing suitable policies and investments. It is worth to mention that the variability of the annual DNI (as shown by historical solar data) plays a significant role in estimating the probability of future performance of a CSP plant, and its influence in the financial contract that the project is likely to receive.

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A detailed knowledge of the incoming DNI is required for an accurate design and optimization of CSP 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 during the duration of the project life, especially for projects with off-take agreements where there is a time-of-day pricing component. In particular, annual variations of solar irradiation may be strong and can harm the return of investment for solar energy projects [3].

Notwithstanding, long time series of solar irradiance and meteorological data are frequently condensed into 1-year series for speeding-up of energy system simulation. Most of simulation tools use a 1-year series (typically at hourly or sub-hourly intervals), designed for reproducing typical months of Global Horizontal solar Irradiance (GHI) and DNI, out of a series of 30 years of actual data, defined as Typical Meteorological Year (TMY) [4]. Because TMY represents typical rather than extreme conditions, it is not suited for designing systems to meet the worst-case conditions occurring at a location [5].

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). 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. 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.

Consequently, lenders may choose to size debt taking into account unfavorable cases of solar resource availability. This is typically assessed by means of the simulation of the energy delivered by the solar plant during years with low solar radiation levels. 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 [6], through the definition of methodologies for generating annual series representative of a probability of exceedance of the solar resource in the location.

The objective of this work is the proposal of a methodology for the generation of meteorological years representative of a given probability of exceedance of annual DNI, which are used to estimate the electric generation output under the corresponding scenario (in particular, in years with low solar radiation levels). This methodology has been developed by a panel of experts under the auspice of AENOR (Spanish Association for Standardization and Certification), and allows the estimation of a CSP plant annual energy yield that is expected to be exceeded in any given year over the life of the debt with a given probability.

The methodology has been compared with respect to the CSP plant yield obtained using a 34-years series of hourly ground measurements of solar irradiance and meteorological parameters.

METHODOLOGY

Measured Data

Solar irradiance and meteorological parameters measured at the Burns station (43.52 ºN, 119.02 ºW) has been selected for this study. This station is located in a cold semi-arid climate and belongs to the University of Oregon Solar Radiation Monitoring Laboratory. The measured data set covers a 34-years period (from 1980 to 2013), and it has been recorded with an hourly interval before 1995, and of 5 minutes afterwards. DNI is measured with an Eppley Normal Incidence Pyrheliometer (NIP), a WMO First Class Pyrheliometer with an associated estimated uncertainty at daily scale of 2%. The radiometers are calibrated on yearly basis with periodic on-site checks with traveling references. Besides quality control procedures applied by the radiometric networks used in this study, the coherence of the data was also visually verified by the authors.

CSP Yield Simulations

A 100 MWe central receiver power plant with 8-h thermal-energy storage has been designed in the location under study. A cost-based optimization has been carried out, resulting in a solar multiple of 2.3 and a heliostat field composed of 10,446 heliostats, with a total effective area of 1,209,350 m^2. The System Advisor Model (SAM), version 2015.6.30, has been used for the estimation of hourly values of the energy produced by the system. SAM is a system performance model incorporating financing options (ranging from residential to utility) developed by the National Renewable Energy Laboratory (NREL), Sandia National Laboratory and the U.S. Department of Energy. SAM uses the TRNSYS [7] software developed at the University of Wisconsin combined with customized components.

Methodology of Meteorological Year's Generation

The objective of the proposed methodology is the generation of a yearly series (at hourly or higher temporal resolution) through the calculation of a standard monthly values set for a specific annual value representative of any desired probability of exceedance.

Annual DNI series are satisfactorily fitted by a Weibull distribution according to different tests [6, 8]. The Weibull distribution, shown in Equation (1), is defined by the following probability density function for x values equal or higher to 0, where κ is the shape parameter, and λ is the scale parameter:

$$f(x) = \frac{\kappa}{\lambda}\left(\frac{x}{\lambda}\right)^{\kappa-1} e^{-\left(x/\lambda\right)^{\kappa}} \tag{1}$$

Where κ and λ are > 0.

The quantile (inverse cumulative distribution) function for the Weibull distribution is shown in Equation (2):

$$Q_{Weibull}(p) = \lambda \cdot \left(-\ln(1-p)\right)^{1/\kappa} \tag{2}$$

The method for calculating monthly DNI values consists in finding those values that minimizes their distance to the corresponding monthly DNI medians (least-squares equation), and which annual cumulative value is, in addition, equal to the annual value representative of a given probability of exceedance. This minimization problem is analytically resolved by means of Lagrange multipliers method [9]. In order to take into account the intra-annual statistics, the least squares equation is conveniently modified with weights determined by the product of the following factors:

- Meteorological variability of each month removing seasonality by means of a clear sky model. This factor is defined as the MAD (Median Absolute Deviation) of the ratio between the monthly DNI and its corresponding monthly clear sky DNI value.
- Individual monthly energy contribution to the total annual radiation. This factor is defined as the mean monthly DNI values normalized to the mean annual DNI value.

The Bird clear sky model [10] is used in this work to remove seasonality. Once the monthly expected values (MEV) are determined, the usual process of minimizing the residuals (finding the closest measured monthly DNI value to the MEV) is applied to determine the constituents months of the meteorological year to be constructed.

The procedure is summarized as follows:

- Step 1. The ratio of available monthly DNI values (AMV) to clear sky DNI monthly values are calculated. This ratio removes the effect of seasonality.
- Step 2. Median absolute deviation (MAD) is calculated for the ratios calculated in Step 1.

- Step 3. The ratio of mean monthly DNI values to the annual mean value is calculated, for quantifying the contribution of each month to the annual DNI target value (representative of the probability of exceedance of annual DNI).
- Step 4. The median DNI values of each month are calculated. Their sum will be subtracted from the annual DNI target value, which has been previously calculated for being representative of the analyzed probability of exceedance.
- Step 5. The weights for distributing the difference between annual DNI target value to be constructed and the sum of median monthly DNI values (step 4) are calculated as the product of the MAD values calculated in step 2 and the ratios calculated in step 3.
- Step 6. The difference between annual DNI target value and the sum of median monthly DNI values (step 4) is distributed according to the weights calculated in Step 5.

Finally, the yearly series is constructed by concatenating months with DNI values close to the monthly values obtained in Step 6.

RESULTS

Annual and monthly values of the CSP plant energy output have been calculated form the hourly CSP yield during the 34 available measured years. Figure 1 shows scatterplot between net energy yield and DNI at annual (left) and monthly (right) scales.

It is appreciated in Fig. 1 that, in some cases, years with different annual DNI values provide similar net energy yields, as a consequence of different intra-annual DNI distributions. For example, years 1980 and 1992 analyzed in this work, with a difference of 9% between their annual DNI values (1,874 and 1,721 kWh/m2 respectively), have similar net annual yields (339 and 334 GW, respectively). Likewise, scatterplots of net energy yield for January and July vs. their corresponding DNI values show similar slope but different dispersions.

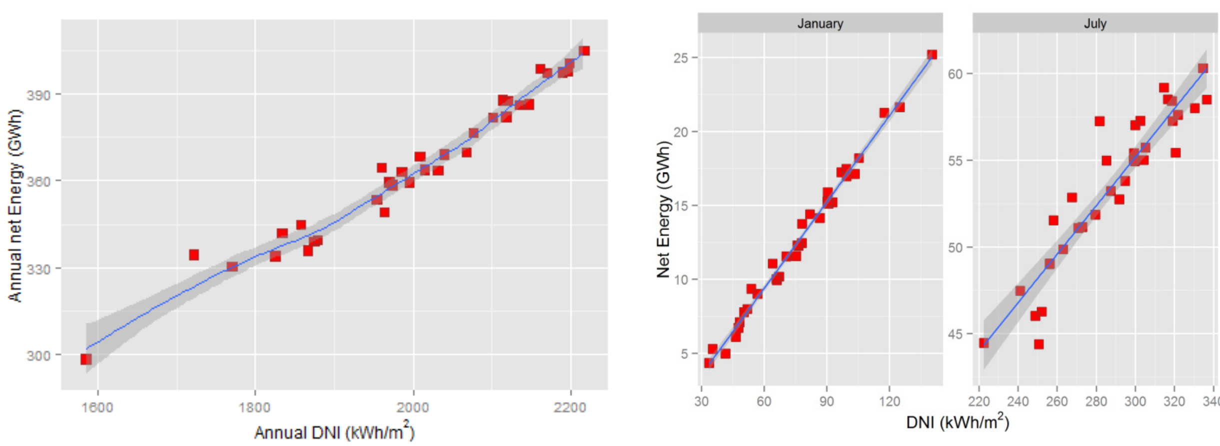

FIGURE 1. Left, scatterplot between annual net energy yield and DNI; right, monthly net energy yield vs. monthly DNI values for January and July.

The fitting of the annual DNI series measured in Burns station to a Weibull distribution provides the following parameter values: κ = 16.9 (dimensionless); λ = 2069.2 kWh/m^2. The application of the methodology for calculating monthly values representative of a given annual probability of exceedance herein presented provides the monthly values for the analyzed probability of exceedances of yearly DNI shown in Table 1.

TABLE 1. Monthly DNI values for Meteorological years representative of several probabilities of exceedance (kWh/m^2).

	P99	**P90**	**P50**
January	55.6	67.0	77.4
February	71.2	86.5	100.5
March	105.8	122.6	137.8
April	119.7	141.3	160.9
May	164.3	183.2	200.4
June	195.0	220.5	243.7
July	231.7	266.0	297.2
August	205.7	237.4	266.2
September	190.2	210.1	228.1
October	120.1	142.5	162.8
November	66.5	73.9	80.6
December	50.9	60.5	69.2
Year	1576.6	1811.5	2024.8

The extensive database available allows the selection of measured months which cumulative value is close to the objective values shown in Table 1. Months selected for representing meteorological years representative of given probabilities of exceedance and their respective net energy yield are shown in Table 2.

TABLE 2. Months selected for representing meteorological years and their net energy yield (GWh).

	P99		**P90**		**P50**	
	Year	Yield	Year	Yield	Year	Yield
January	1988	9.02	1990	10.18	2008	12.45
February	1998	11.87	1984	17.64	1997	16.47
March	1980	18.55	2009	22.02	2002	25.73
April	1996	19.97	2012	26.95	1994	30.27
May	1991	29.18	2005	32.83	1983	38.22
June	1992	39.13	1988	38.28	1999	45.21
July	1982	44.48	2007	52.86	1998	55.04
August	1999	41.84	1982	46.58	1985	49.42
September	1992	41.13	1981	40.32	2012	44.71
October	1992	23.55	1985	26.8	1997	28.99
November	1992	10.07	1990	10.17	2000	13.31
December	1995	6.38	1982	9.25	1993	10.28

Figure 2 shows Annual net energy yield (red lines) along with the estimated probabilities of exceedance (green lines) obtained with meteorological years constructed following the methodology herein presented.

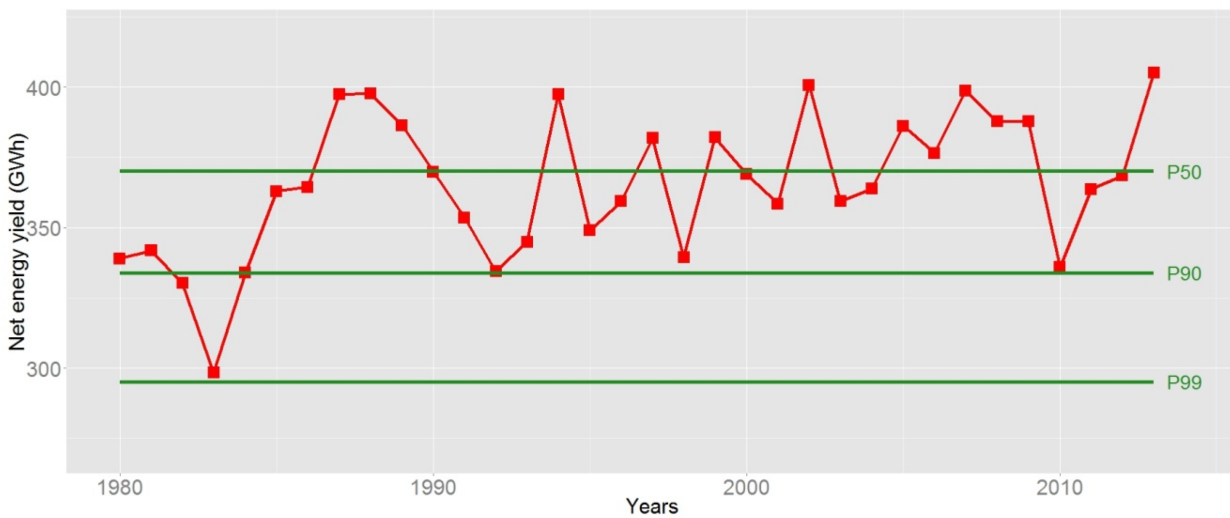

FIGURE 2. Annual net energy yield series (red line), and P99, P90 and P50 values (green lines)

Both P50 and P90 values calculated with the methodology herein presented (370.1 and 331.9 GWh, respectively) are close to the corresponding probabilities of exceedance calculated with the 34-year series of net energy yield (364.1 and 334.9 GWh, respectively). The P99 value calculated with the methodology (295.2 GWh) is far from the corresponding P99 value calculated with the 34-year series (308.9 GWh). This is due to the fact that calculating probabilities of exceedance in a discrete dataset assigns 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.

CONCLUSIONS

In this study, a methodology for generating meteorological years representative of a given probability of exceedance of annual DNI is presented, which can be used as input in risk assessment for securing competitive financing for solar power projects. This methodology is based on the variability and seasonality of monthly DNI values and uses as boundary condition the annual DNI value representative for any desired probability of exceedance. The results are compared against a 34-years series of net energy yield calculated at hourly intervals with measured meteorological and solar irradiance data.

This work also explores the relation between DNI and net energy yield of a CSTP plant, based on a 34-years measured DNI and meteorological parameter series. It has been found that relation between annual net energy yield and DNI is not univocal, highlighting the need of defining monthly DNI values in the generation of meteorological years representative of a given probability of exceedance of annual DNI. Scatterplots between monthly net energy yields and DNI show different dispersions throughout the year, being higher at summer months (reflecting the effect of their daily distributions and different number of sunny days straight).

From the results of this work, it is recommended to infer extreme values from the analytical distribution function obtained from the available database (with respect to the use of just available dataset) in the risk assessment for securing competitive financing in CSTP projects. Future works will include the extension of the methodology for generating a meteorological year representative of a given probability of exceedance of annual GHI, and its ability to evaluate the probabilistic assessment of photovoltaic (PV) plants yield.

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REFERENCES

1. C.K. Ho and G.J. Kolb, J. Sol. Energy Eng. **132**, 031012 (2010).
2. C.M. Fernández-Peruchena, M. Gastón, M. Sánchez, J. García-Barberena, M. Blanco, A. Bernardos, Sol. Energy **120**, 244–256 (2015).
3. S. Lohmann, C. Schillings, B. Mayer, R. Meyer, Sol. Energy **80**, 1390–1401 (2006).
4. L. Hall, R. Prairie, H. Anderson, E. Boes, "Generation of Typical Meteorological Years for 26 SOLMET stations" Sandia National Lab., Albuquerque, NM (No. SAND78-1601) (1978).
5. M. Sengupta, A. Habte, S. Kurtz, A.P. Dobos, S. Wilbert, E. Lorenz, T. Stoffel, D. Renné, C. Gueymard, D. Myers, S. Wilcox, P. Blanc, R. Pérez, "Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications" National Renewable Energy Laboratory, Golden, CO. (No. NREL/TP-5D00-63112) (2015).
6. C.M.F. Peruchena, L. Ramírez, M.A. Silva-Pérez, V. Lara, D. Bermejo, M. Gastón, S. Moreno-Tejera, J. Pulgar, J. Liria, S. Macías, R. Gonzalez, A. Bernardos, N. Castillo, B. Bolinaga, R.X.. Valenzuela, L.F. Zarzalejo, Sol. Energy **123**, 29–39 (2016).
7. M.J. Atkins, M.R.W. Walmsley, A.S. Morrison, Energy **35**, 1867–1873 (2010).
8. C.M.F. Peruchena, L. Ramírez, M.A. Silva-Pérez, V. Lara, D. Bermejo, M. Gastón, S. Moreno, J. Pulgar, J. Liria, S. Macías, R. Gonzalez, A. Bernardos, N. Castillo, B. Bolinaga, R.X.. Valenzuela, L.F. Zarzalejo, "A methodology for calculating percentile values of annual direct normal solar irradiation series." In *SOLARPACES* 2015: International Conference on Concentrating Solar Power and Chemical Energy Systems. Vol. 1734. No. 1. AIP Publishing, 2016.
9. V. Lara-Fanego, J. Pulgar, C.M. Fernández-Peruchena, M. Gastón, S. Moreno, L. Ramírez, R.X. Valenzuela, D. Bermejo, M. Silva, M. Pavon, A. Bernardos, L. Zarzalejo, S. Macías, "A novel procedure for computing solar irradiance TMYs", in: *SolarPACES Conference Proceedings 2016*. Abu Dhabi, United Arab Emirates.
10. Bird, R.E., Hulstrom, R.L., 1981. Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces (No. SERI/TR-642-761). Golden, Colorado.