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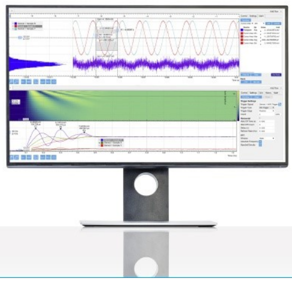

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Statistical Analysis of CSP Plants by Simulating Extensive Meteorological Series

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Abstract. The feasibility analysis of any power plant project needs the estimation of the amount of energy it will be able to deliver to the grid during its lifetime. To achieve this, its feasibility study requires a precise knowledge of the solar resource over a long term period. In Concentrating Solar Power projects (CSP), financing institutions typically requires several statistical probability of exceedance scenarios of the expected electric energy output. Currently, the industry assumes a correlation between probabilities of exceedance of annual Direct Normal Irradiance (DNI) and energy yield. In this work, this assumption is tested by the simulation of the energy yield of CSP plants using as input a 34-year series of measured meteorological parameters and solar irradiance. The results of this work show that, even if some correspondence between the probabilities of exceedance of annual DNI values and energy yields is found, the intra-annual distribution of DNI may significantly affect this correlation. This result highlights the need of standardized procedures for the elaboration of representative DNI time series representative of a given probability of exceedance of annual DNI.

INTRODUCTION

Concentrating Solar Power (CSP) technologies collect and concentrate the direct component of solar radiation onto a small area using mirrors or lenses. The concentrated solar radiation is used to generate electric power through its conversion into heat by means of a thermodynamic cycle. In CSP technologies, as in any other capital extensive technology, plant projects have to be evaluated through simulation prior to its real implementation to reduce financial risk. The feasibility analysis of any power plant project requires the estimation of the amount of energy that it will be able to deliver to the grid during its lifetime.

A detailed knowledge of the Direct Normal Irradiance (DNI) is a critical point to perform an economical feasibility analysis of a CSP plant, as it is the most determining variable in the final energy yield. Moreover, due to the significant short-term and long-term variability in DNI, CSP analysts must obtain detailed DNI data time series, and not just mean annual values. Nowadays, the feasibility analysis of a CSP plant is usually carried out by simulating the plant performance using a Typical Meteorological Year (TMY) of hourly values of DNI and other meteorological parameters as input.

A TMY represents statistically the typical meteorology of the project location. Notwithstanding, annual variations of DNI may be strong and can seriously affect the return of investment for CSP projects; consequently, CSP financing is usually based on a statistical assessment of the solar resource. 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) [1]. In most cases, a long time series of measured solar irradiance is not available, except if these data are modelled (in which case its uncertainty can be significant).

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In particular, average and *near-worst* cases of solar resource availability are often analyzed in order to ensure the viability of the project. Frequently, these cases are evaluated by *probability of exceedance* scenarios (P-levels, from now on), which provide an estimate of the electric generation output that the solar resource consultant expects to be exceeded in any given year over the life of the debt with 50% confidence (P50), 90% confidence (P90) and 99% confidence (P99). This approach provides the theoretical average and floor output levels based on a probability and time span [2]. It is usually recommended to include measures from at least 15 years to build the TMY and the time series corresponding to P90 or P95. The uncertainty of the solar resource assessment (and consequently of the electricity yield estimates) is reduced as the number of years increase [3].

It is usually accepted that there is a correspondence between DNI and electricity yield P-levels (i.e., the energy yield P90 is obtained by simulating with the DNI P90) [4]. The aim of this paper is to verify the correspondence between P-levels for the solar resource and P-levels for the annual energy yield. These P-levels are analyzed from a large database (34 years of measurements) in Burns (Oregon, USA) and compared with the simulated annual energy yields of two CSP plants (Central Receiver and Parabolic Trough) in this location.

METHODS

Measured Data

Solar irradiance and meteorological parameters measured by the Burns meteorological station (43.52 ºN, 119.02 ºW) have 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 (http://solardat.uoregon.edu/). The measured data set covers a 34-years period (from 1980 to 2013), 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 pyrheliometer is calibrated on yearly basis with periodical on-site checks with traveling references.

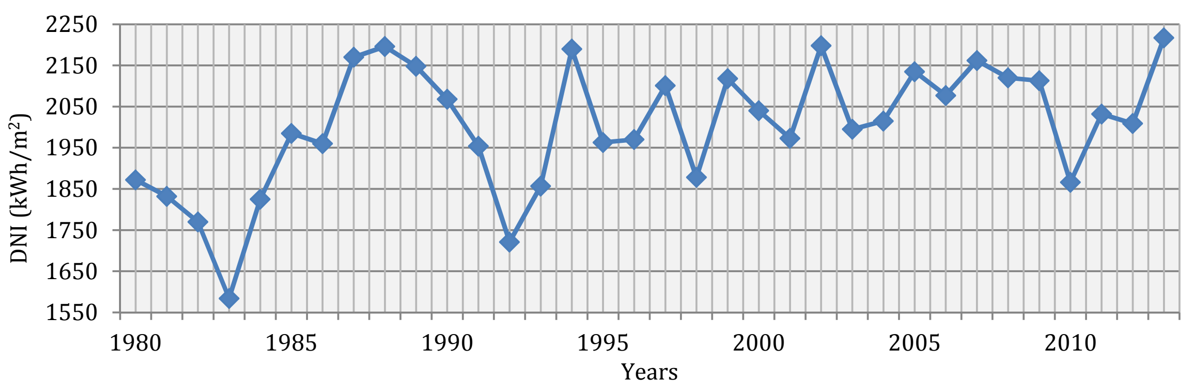

FIGURE 1. Annual DNI (kWh/m^2) measured in Burns station (1980-2013).

CSP Yield Simulations

The System Advisor Model 2015.6.30 (SAM, https://sam.nreal.gov/) has been used for the simulations 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, http://www.nrel.gov/), Sandia National Laboratory and the U.S. Department of Energy. SAM uses the TRNSYS software [5], a validated time-series simulation program that provide the performance of photovoltaic, concentrating solar power, water heating systems, and other renewable energy systems using hourly resource data. This program, designed by the NREL, allows to the user to define a solar field in different sorts of technologies such as Parabolic Trough, Central Receiver, Dish Stirling and Linear Fresnel.

This study aims at two technologies with currently large worldwide implementation: Central Receiver and Parabolic Trough. 100 MWe power plants with 8 equivalent hours of thermal energy storage have been designed in the location under study. A cost-based optimization has been carried-out in each technology, resulting in:

- A **Central Receiver (CR)** power plant with a solar field composed of 10,446 heliostats, a total reflective area of 1 209 350 m^2 and a solar multiple of 2.3.
- A **Parabolic Trough (PT)** power plant with 337 loops, a total reflective area of 1 101 990 m^2 and solar multiple of 2.4.

RESULTS

Figure 2 shows the scatter plot of annual energy yield vs. annual DNI in Central Receiver. A good linear relation between annual DNI and annual energy yield is observed, with some exceptions. The years marked with blue diamonds have a very similar DNI but different energy yields and the green marked triangles have different DNI and similar energy yield.

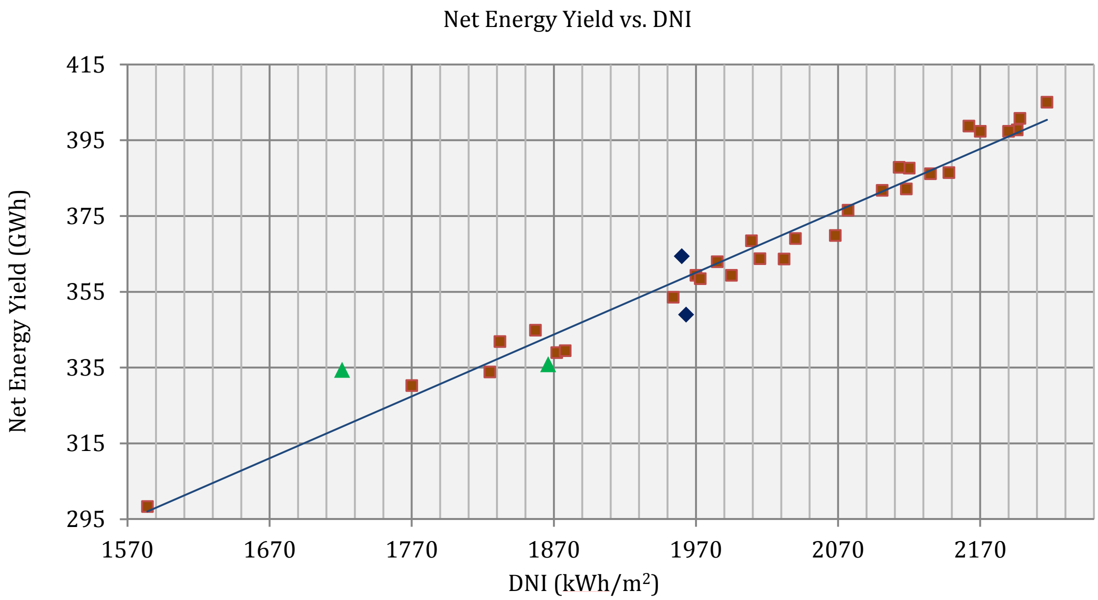

FIGURE 2. Scatter plot of DNI and net energy yield in Central Receiver.

Fig 3 shows the monthly DNI and energy yields in 1986 and 1995, which have a very similar DNI (1960 kWh/m^2 in 1986 and 1963 kWh/m^2 in 1995) but different energy yields (364.4 GWh in 1986 and 349.0 GWh in 1995) as a consequence of their different intra-annual DNI distributions. In particular, different DNI values found in August (258.7 kWh/m^2 in 1986 and 300.8 kWh/m^2 in 1995) led to similar energy yields (50.48 GWh in 1986 and 53.10 GWh in 1995). Furthermore, in April 1986, the monthly DNI is 180.4 kWh/m^2, and in April 1995, 155.5 kWh/m^2 with a difference of 16.01 % between them. However, the difference of energy yield between both years is 38.02 %, showing a non-linear relationship between annual DNI and energy yield.

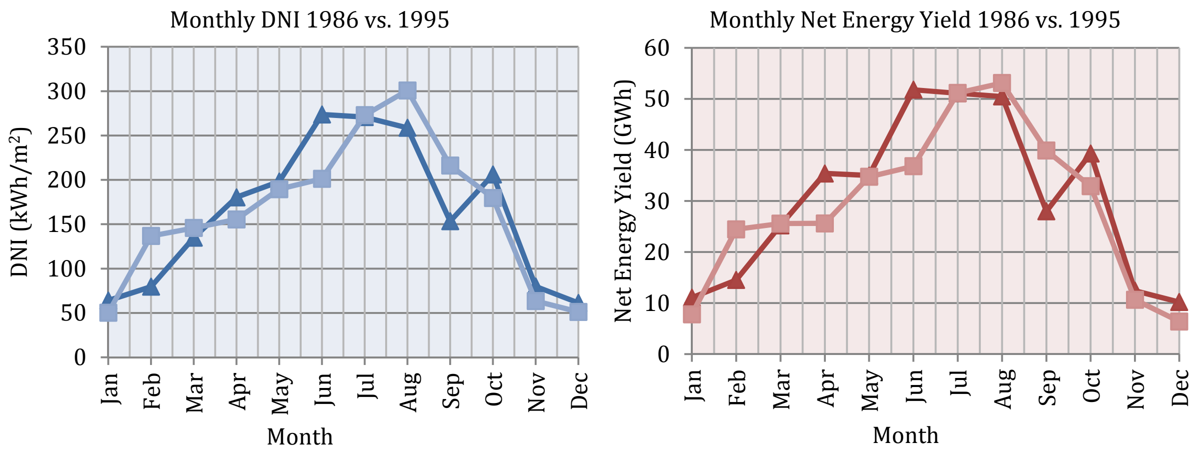

FIGURE 3. Monthly DNI series in 1986 (dark blue triangles) and 1995 (light blue squares) and net energy yield in 1986 (dark red triangles) and 1995 (light red squares).

Fig 4 shows the monthly DNI and energy yields for 1984 and 1992 (which are highlighted in Fig. 2 as blue squares). In this case, different annual DNI values (1825 kWh/m^2 in 1984 and 1721 kWh/m^2 in 1992) led to similar annual energy yields (333.9 GWh in 1984 and 334.4 GWh in 1992). It is worth to highlight that the highest net energy yield in 1992 corresponds to May, which overcomes the yield of July and August with lower DNI.

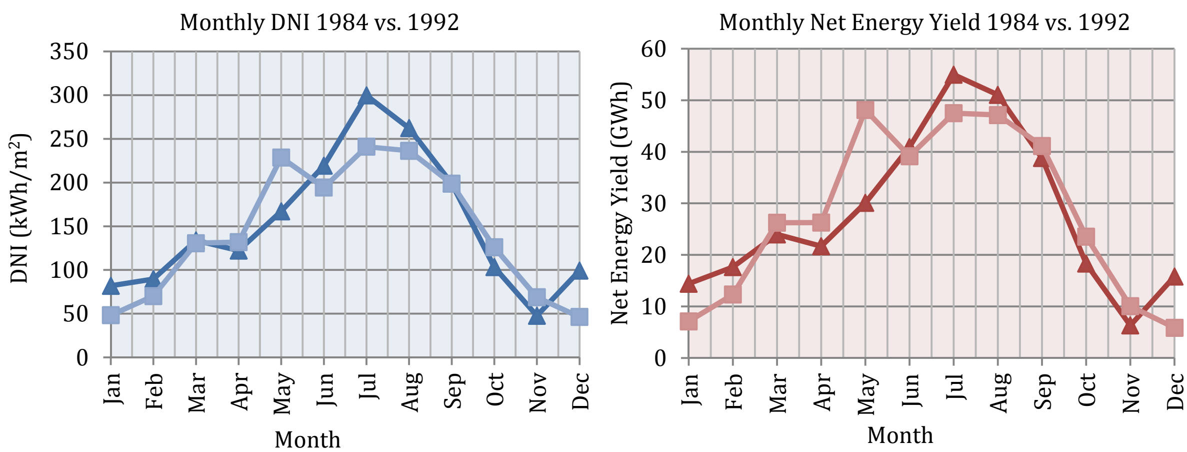

FIGURE 4. Monthly DNI series in 1984 (dark blue triangles) and 1992 (light blue squares) and net energy yield in 1984 (dark red triangles) and 1992 (light red squares).

In July and August there is a large number of days with significant solar field defocusing caused by the saturation of the thermal storage. The plant is generating electricity at rated power and the thermal energy storage is full, so the solar field has to be partially defocused. Defocusing in July and August is more important than in May, as shown in Fig 5. This suggest that the intra-daily temporal distribution of the DNI results in a better utilization of the solar resource.

The monthly energy yield vs. the monthly DNI for all the May and July months of the database are represented in Fig. 6. In general, it seems to be a fairly linear correspondence between DNI and energy yield. However, May 1992 (marked with a blue triangle) deviates from the general trend showing a higher net energy yield. This is an example of months that could affect the estimation of energy produced by the power plant if chosen to build the TMY. This result highlights the care that must be taken in the design of TMY and P-levels series with typical months, avoiding the use of 'outliers' if the statistical correspondence between energy yield and DNI is to be assumed.

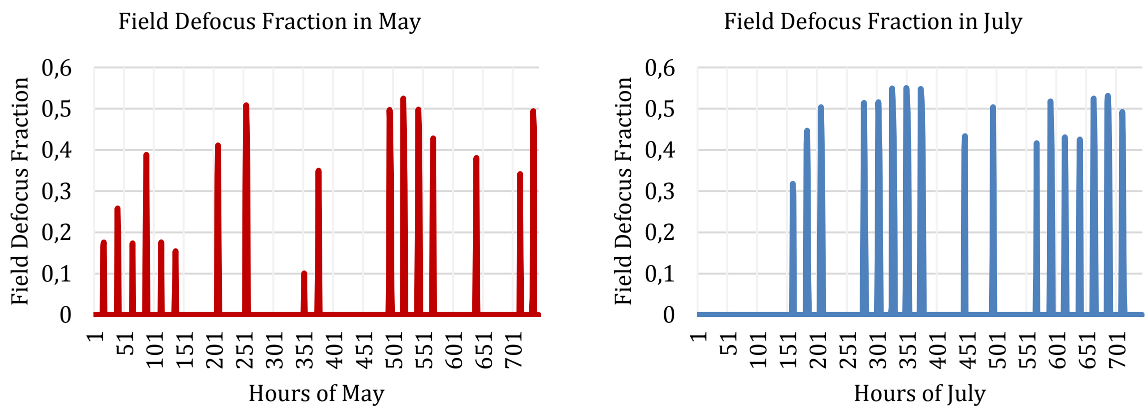

FIGURE 5. Field defocus fraction in May and July in Central Receiver.

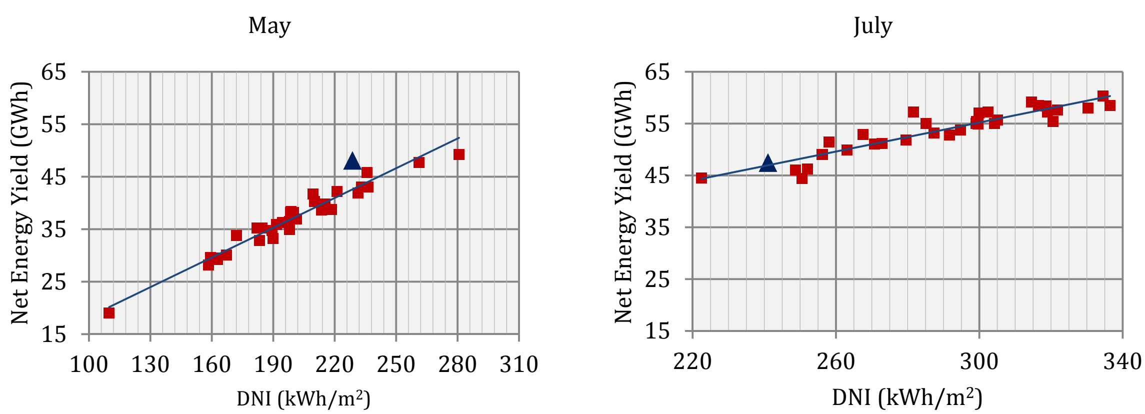

FIGURE 6. Scatter plot of DNI and net energy yield of May (left) and July (right) from 1980 to 2013 in Central Receiver.

Figure 7 shows the scatter plot of annual energy yield vs. annual DNI for the Parabolic Trough (PT) plant. A good correlation between annual DNI and annual energy yield is observed. Notwithstanding, it is worth to highlight that the linear relation is better in Central Receiver than in Parabolic Trough (the values of the correlation coefficients, R^2,are 0.9613 and 0.9265 respectively). In addition, as in the case of Central Receiver, some exceptions are observed. There are years which have exactly the same energy yields and different DNI (years 1992 and 1993) marked with green triangles. On the other hand, there are years with similar DNI but different energy yields, marked with blue diamonds (years 2000 and 2011).

The lower energy yield of the PT plant compared to the CR one is due to different factors, including the penalization of the optical efficiency of the solar field at this relatively high latitude and the lower efficiency of the power cycle in the PT plant, derived from the lower HTF temperature achievable in thermal oil based PT plants.

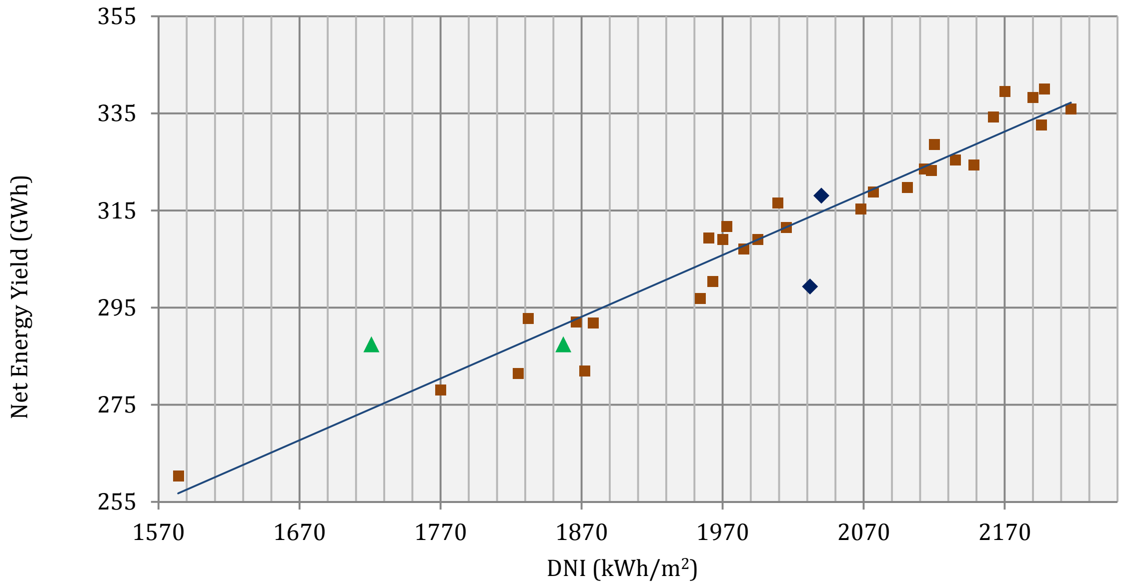

FIGURE 7. Scatter plot of DNI and net energy yield in Parabolic Trough.

Fig 8 shows the monthly DNI and energy yields in 1992 and 1993, which have different DNI (1721 kWh/m^2 in 1992 and 1857 kWh/m^2 in 1993) but exactly the same energy yield (287.5 GWh) as a consequence of their different intra-annual DNI distributions. For instance, in May 1992 the DNI is 228.7 kWh/m^2 and 194.4 kWh/m^2 in 1993. These values lead to different energy yields (47.6 GWh in 1986 and 35.9 GWh in 1995), with non-linear relation (a 15 % of difference in DNI results in a difference of approximately 25 % in energy yield).

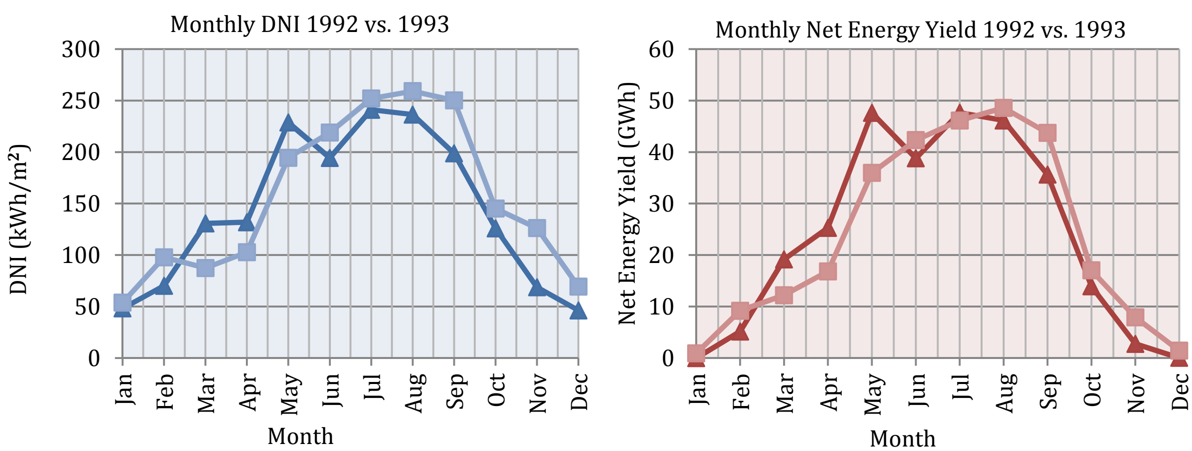

FIGURE 8. Monthly DNI series in 1992 (dark blue triangles) and 1993 (light blue squares) and net energy yield in 1992 (dark red triangles) and 1993 (light red squares).

Fig 9 shows the contrast between May (R^2 = 0.924) and July (R^2 = 0.808). Note the point marked with a blue triangle, corresponding to May 1992. In this technology, this month is again an ‘outlier’.

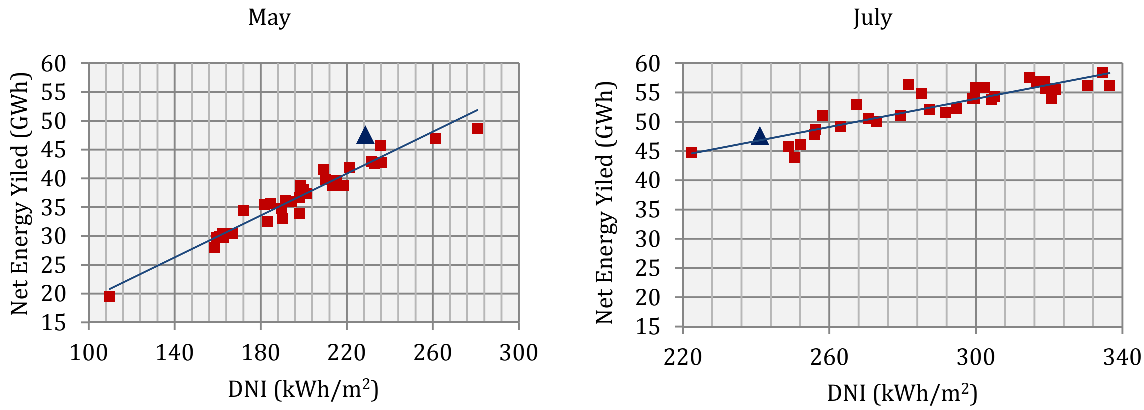

FIGURE 9. Scatter plot of DNI and net energy yield of May (from 1980 to 2013) in Parabolic Trough.

Fig 10 shows the monthly DNI and energy yields in 2000 and 2011, which have similar DNI (2040 kWh/m^2 in 2000 and 2032 kWh/m^2 in 2011) but different energy yield (318.1 GWh in 2000 and 299.4 GWh in 2011) as a consequence of their different intra-annual DNI distributions. The analysis of the distribution of DNI from 2011 shows that this year has a higher radiation in winter than in 2000, but almost the rest of the year, 2000 has a higher radiation than in 2011, in periods of the year where the efficiency of the plant is higher. This provokes a better utilization of the plant and finally, a higher energy yield.

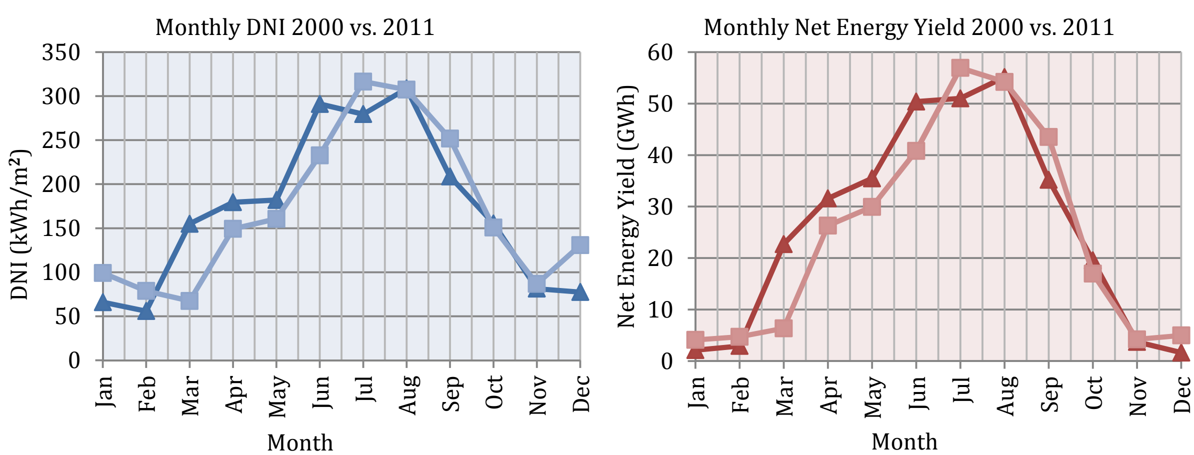

FIGURE 10. Monthly DNI series in 2000 (dark blue triangles) and 2011 (light blue squares) and net energy yield in 2000 (dark red triangles) and 2011 (light red squares).

Table 1 shows the values of DNI and energy yield for different P-levels obtained from the analysis in Central Receiver. P-levels have been calculated by means of the ECDF. Two years with annual DNI values -next lower and next higher to the corresponding P-levels- have been chosen for this purpose. The goal is to recognize if the P-level of energy yield is between these values. A good correlation is found between DNI P-levels and energy yield P-levels, being the uncertainty greater at lower DNI values. For example, the P50 has a clear correspondence. However, other P-levels such as P90 or P10 show greater differences, probably caused by different intra-annual DNI distribution.

Table 2 shows the values of DNI and energy yield for different *P*-levels obtained from the analysis in Parabolic Trough, as well as the corresponding values for the years with DNI values close to the corresponding P-levels of DNI. The results regarding the correspondence between DNI and energy yield P-levels are similar for CR and PT, although slightly better for CR.

TABLE 1. Comparison between DNI P-levels and energy yield P-levels in Central Receiver.

P-Level	P95		P90		P50		P10		P5	
DNI (kWh/m^2)	1730.8		1819.5		2012.0		2190.6		2197.6	
Energy Yield (GWh)	331.0		334.4		364.1		397.9		400.4	
Year	**1992**	**1982**	**1982**	**1984**	**2012**	**2004**	**1987**	**1994**	**1988**	**2002**
DNI (kWh/m^2)	1721	1770	1770	1825	2009	2015	2190	2196	2196	2198
Energy Yield (GWh)	334.4	330.3	330.3	333.9	368.5	363.8	397.4	397.8	397.8	400.8

TABLE 2. Comparison between DNI P-levels and energy yield P-levels in Parabolic Trough.

P-Level	P95		P90		P50		P10		P5	
DNI (kWh/m^2)	1730.8		1819.5		2012.0		2190.6		2197.6	
Energy Yield (GWh)	278.8		281.9		311.6		336.1		340.0	
Year	**1992**	**1982**	**1982**	**1984**	**2012**	**2004**	**1987**	**1994**	**1988**	**2002**
DNI (kWh/m^2)	1721	1770	1770	1825	2009	2015	2190	2196	2196	2198
Energy Yield (GWh)	287.5	278.1	278.1	281.4	316.5	311.5	339.5	338.3	332.6	340.0

CONCLUSIONS

The analysis of the energy yield for 34 years of DNI measurements shown in this work indicates that the correspondence between the probabilities of exceedance of annual DNI values and energy yields is fairly good from the statistical point of view. For the cases considered in this analysis, this correspondence is slightly better in Central Receiver than in Parabolic Trough technology. Care should be taken when building annual meteorological series for representing probability of exceedance scenarios, since the intra-annual distribution of DNI may significantly affect the energy yield estimates. Atypical months ('outliers') can significantly affect the energy yield estimates and, thus, the correspondence between annual energy yield and DNI P-levels. These results highlight the need to define and validate standardized procedures for the elaboration of representative DNI time series based at least on monthly values.

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REFERENCES

1. A.P. Dobos, P. Gilman, M. Kasberg, P50/P90 Analysis for Solar Energy Systems Using the System Advisor Model: Preprint (No. NREL/CP-6A20-54488). National Renewable Energy Laboratory (NREL), Golden, CO. (2012)
2. Fitch Ratings. "Rating Criteria for Solar Power Projects Utility-Scale Photovoltaic, Concentrating Photovoltaic and Concentrating Solar Power". (2016)
3. C. M. F. Peruchena, L. Ramírez, M.A. Silva-Pérez, ,... & R. Gonzalez, *Solar Energy*, 123 (2016), 29-39
4. F. Vignola, C. Grover, N. Lemon, A. McMahan, *Solar Energy* 86, (2012), 2218–2229.
5. M.J. Atkins, M.R.W. Walmsley, A.S. Morrison, *Energy* 35 (2009), 1867–1873