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Impact of the Intra-Day Variability of the DNI on the Energy Yield of CSP Plants

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Abstract. The operation and the electricity yield of CSP plants in two days with the same daily-accumulated DNI, even with the same Aperture Normal Irradiance (ANI) can be very different depending on other parameters such as the variability and distribution of the solar radiation. In this paper, we intend to quantify the impact of the intra-daily variability of the DNI on the production of CSP plants. To that end, we use the ND model [1] to generate several synthetic years with similar distribution and daily energy to a reference measured year but different levels of intra-daily variability. We use System Advisor Model (SAM, https://sam.nrel.gov/) to simulate the performance of two parabolic trough (PT) plants, with and without thermal storage and common configurations for the location of Seville, Spain. To test the influence of the DNI variability, we simulate the measured and the synthetic years and we compare the daily gross power produced. As result, a clear decrease in the gross production of the PT plant without TES system is observed when the intra-daily variability increases, with daily average differences of 47% respect to the case with lowest variability. This difference is reduced with the use of the TES system to 6 %, damping the dynamic effects of the DNI variability on the global response of the plant.

INTRODUCTION

The electricity yield of a given Concentrated Solar Power (CSP) plant depends mainly on the amount of DNI available. However, the operation and the electricity yield of CSP plants in two days with the same daily-accumulated DNI, even with the same ANI can be very different. Its intra-daily temporal distribution of the solar radiation also has a significant impact, not only due to time-related geometrical effects (incidence angle, daylight time), but also to the interaction between the dynamics of the DNI and of the plant itself. On the global plant response, the use of a Thermal Energy Storage (TES) system reduces the dynamic effects due to solar irradiance variations [2]. But, in both cases (with or without TES system), the dynamic effects of the intra-daily variability are interesting from the control strategies point of view [3]. Optimizing the plant operation increases the collected solar energy (reducing defocusing instances) and hence, the electricity yield of the plant [4]. Thus, the knowledge of relevant intra-daily features of the solar resource can be useful to assess the performance of a CSP plant [5] or to define operating strategies based on the prediction of these features [6].

The economic risk of a CSP plant project is usually evaluated through synthetic solar radiation representative series which have been built based on annual, monthly or daily data [7-8] where the intra-daily behavior of the resource is not considered. The consideration of the intra-daily features in the solar radiation assessment studies could help to reduce the uncertainty on the feasibility analysis of the plants. In this paper, we intend to quantify the impact of the intra-daily variability of the DNI on the production of CSP plants. To that end, we use the ND model [1] to generate several synthetic years with similar distribution and daily energy to a reference measured year but different levels of intra-daily variability. We use System Advisor Model (SAM, https://sam.nrel.gov/) to simulate the performance of two parabolic trough (PT) plants, with and without thermal storage and common configurations for the location of

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Seville, Spain. To test the influence of the DNI variability, we simulate the measured and the synthetic years and we compare the daily gross power produced.

METHODOLOGY

We use an annual set DNI measurements recorded in Seville (37.40° N, 6.01° W) for 2016 by the Group of Thermodynamics and Renewable Energies (GTER) of the University of Seville as reference to generate synthetic DNI sets. The DNI daily features of this year are characterized by three daily indexes in terms of energy, variability and distribution [9] through the daily transmittance index, k_b^d; the variability index, VI; and the morning fraction index, F_m respectively following next equations

$$k_b^d = \frac{Ibn^d}{{Ibn_{cs}}^d} \ , \qquad (1)$$

$$VI = \frac{\sum_{i=2}^{n}\sqrt{\left({I_{bn}}^{i}-{I_{bn}}^{i-1}\right)^2+\Delta t^2}}{\sum_{i=2}^{n}\sqrt{\left({I_{bn_{cs}}}^{i}-{I_{bn_{cs}}}^{i-1}\right)^2+\Delta t^2}} \qquad (2)$$

$$F_m = \frac{Ibn_{md}^d}{Ibn^d} \qquad (3)$$

where Ibn^d is the daily DNI and ${Ibn_{cs}}^d$ is the daily DNI under clear sky conditions. $I_{bn_{cs}}$ is the enveloping clear sky direct normal irradiance [1], the subscript i represents the time instant, Δt refers to an interval of one minute, n is the number of 1-min intervals of the considered day. Ibn_{md}^d is the DNI recorded from the sunshine to the solar noon. We use the ND model [1] to generate four synthetic annual 1-min DNI sets.

The ND model relies in the normalization of the daily DNI curve by the clear-sky envelope, creating daily dynamic paths from observed DNI data. The method transforms each daily 1-min DNI curve into a dimensionless curve where the normalized time and the DNI range from 0 to 1. For the synthetic generation of 1-min data, we first calculate the clear sky DNI envelopes, then we generate a database of dimensionless daily curves based on an extensive 1-min database. In this case, we use 15 years of measured 1-min DNI data from GTER database for the location of Seville. For this end, we normalize the measured data in terms of time and energy. We also categorize each day in terms of energy, variability and distribution using the k_b^d, the VI and the Fm (Eq 1-3) Once an extensive database of 1-min data is normalized and categorized, for the generation of synthetic 1-min data for a given day, we only require, as input, daily information about the energy, variability and distribution. With that information, we seek for the most similar day in the normalized database and we combine envelopes and dimensionless daily DNI curves to obtain the synthetic data in the 1-min resolution.

From the daily features of the DNI of the year 2016, four annual synthetic sets are generated by means of the ND model in 1-min resolution. These datasets have similar k_b^d and F_m values to the measured 2016 set but different VI values. We manually select the values of the daily VI index from four intervals:

- Low values: Daily VI index in the 1-min resolution between [0,2];
- Medium values: Daily VI index in the 1-min resolution between [4,6]
- High values: Daily VI index in the 1-min resolution between [9,11]
- Very high values: Daily VI index in the 1-min resolution between [14,16]

We evaluate the impact of the variability on the production of a PT plant by analyzing the gross electrical power produced by two PT plants, with and without Thermal Energy Storage (TES). We simulate in SAM using the four synthetically generated years as input. We select two PT plants similar to operational plants sited in the South of Spain and currently in operation as reference models: Andasol 3 and Solnova 1. Both plants have an installed capacity of 50 MWe of net nominal power and use parabolic trough technology to collect the solar energy. The main characteristics of these plants are summarized in Table 1.

TABLE 1. Main technical data used in SAM to model the plants. PTP0 and PTP7.5 models are based on the characteristics of SOLNOVA 1 and ANDASOL 3, respectively, both plants located in Spain.

Parameter	**PTP0**	**PTP7.5**
Net output at design (MWe)	50	50
Collector type	EuroTrough ET150	EuroTrough ET150
Receiver type	Schott PTR70 2008	Schott PTR70 2008
Number of loops	90	156
Collectors per loop	4	4
Solar field aperture area (m2)	300,000	510,120
HTF	Therminol VP-1	Therminol VP-1
Design loop outlet Temp. (ºC)	391	391
Thermal Storage Capacity (full-load equivalent hours)	0	7.5
TES type and medium	-	Two-tank, Hitec Solar Salt

Hereinafter, the Andasol 3 plant model is called PTP7.5 and the Solnova 1 plant model is called PTP0. The operation strategy of the PTP7.5 TES has been defined to provide full power output during the maximum possible time. The purpose of defining this operating strategy is to use all the remaining energy in the storage tanks after the sunset, so that the TES is empty at sunrise. The large capacity of the PTP7.5 TES permits the generation of electricity during the first hours of the next day. To avoid the effect of the energy collected during a given day on the assessment of the next day, the electricity yield is computed from 4:00 a.m. to 3:50 a.m. of the next day.

RESULTS AND DISCUSSION

We evaluate the daily values of gross electrical power (GP_d) produced by the PT plants with and without thermal storage as function of the low variability DNI set. In Figure 1a, we represent the GP_d obtained by simulating the measured data set versus the GP_d produced with the synthetic year with low VI for the PT plant without thermal storage, showing that Seville is a location with very infrequently variability days. Figures 1b, 1c and 1d represent the GP_d produced with the synthetic year with low variability versus the GP_d produced with the synthetic year with medium, high and very high variability for the PTP0. In Figure 2 we present the same data but for the PTP7.5. (PT plant with thermal storage).

Due to the nature of the ND algorithm, we can obtain, in some cases, significant differences in the daily cumulative solar radiation value of the synthetic datasets in comparison to the measured dataset. In those cases, the impact of the variability of the solar radiation may not be identified. To avoid that issue, we only evaluate those days in which the difference between the measured and synthetic daily DNI cumulative values are lower than 1 kWh.

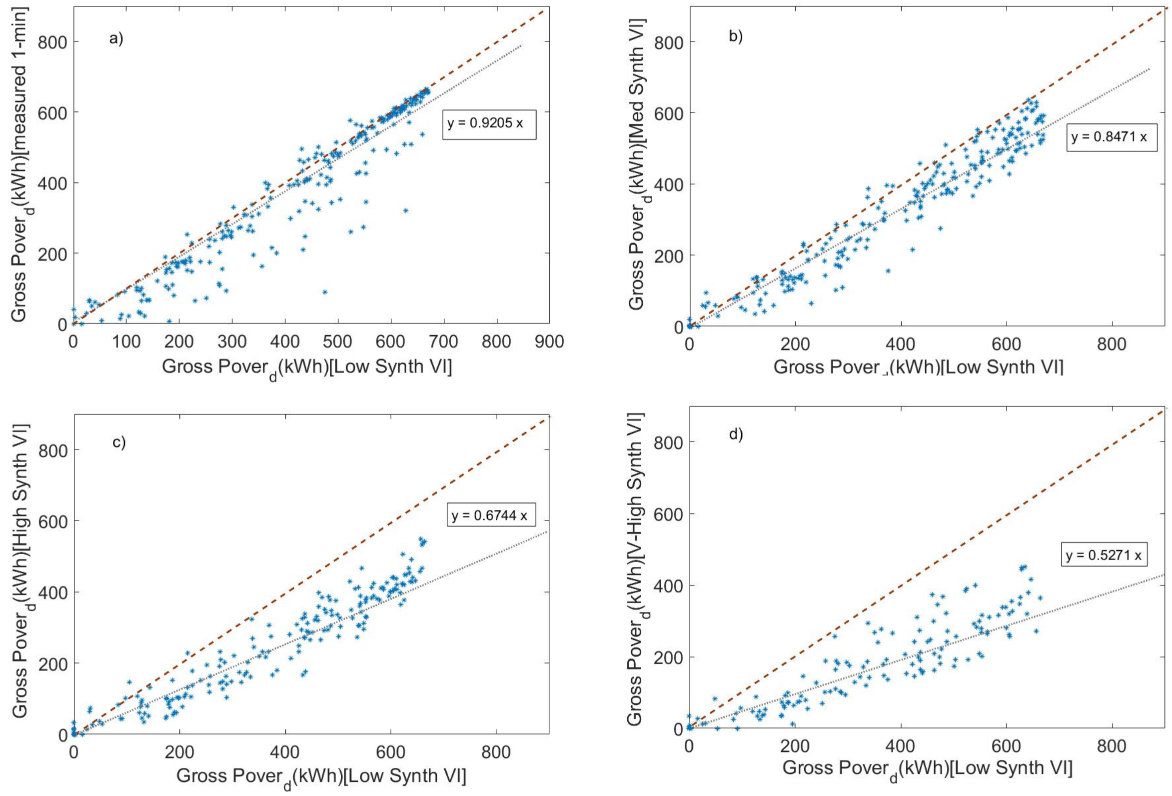

FIGURE 1. GP_d produced by the PT plant without TES as a function of the low variability DNI set.

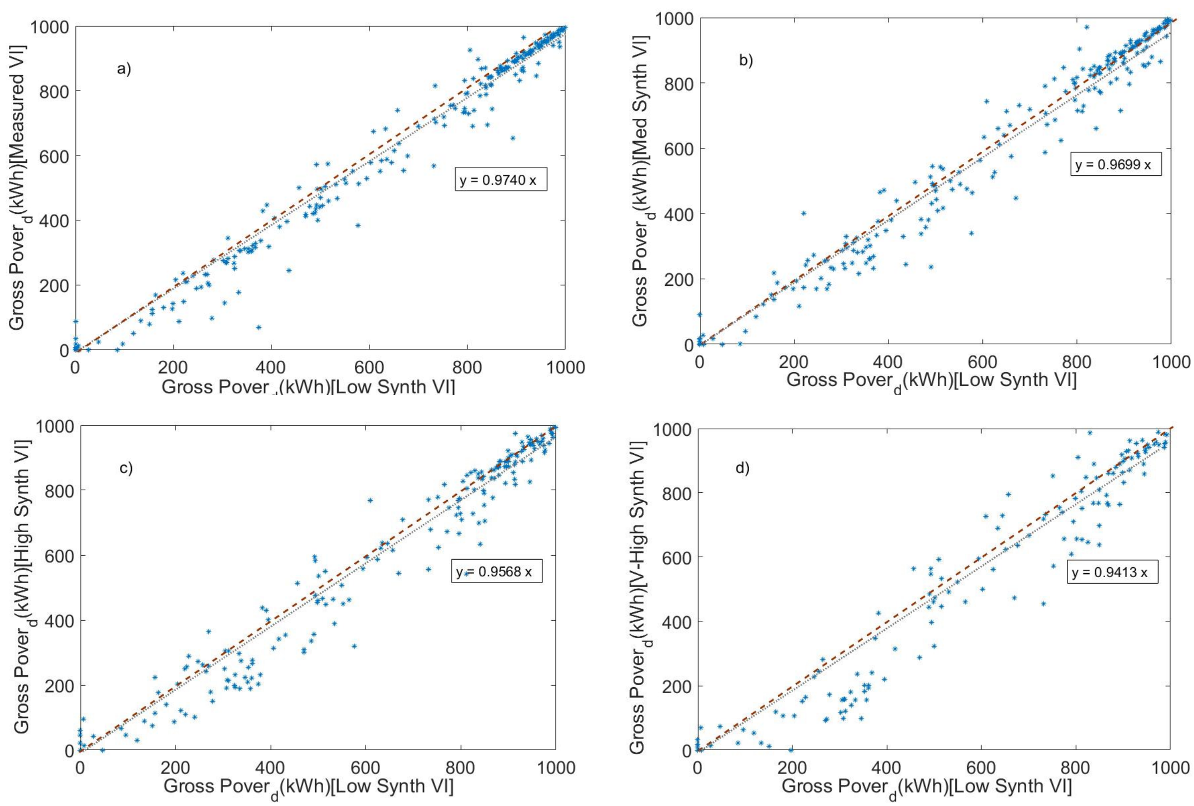

FIGURE 2. GP_d produced by the PT plant with TES as a function of the low variability DNI set.

From Figure 1, we can observe that in the case of the plant without thermal storage, the greater the daily variability, the lower the gross production for the same daily cumulative value of DNI. In the case of the plant with thermal storage (Figure 2), the impact of the variability on the gross production is significantly reduced. This tendency can be quantified from a linear regression fit using least square procedure. In Table 2, we resume the quantification of the decrease in the gross production of a CSP plant with and without thermal storage as a function of the variability of the solar radiation, considering the daily average difference between both cases as the slope of the linear regression. We can observed, an average daily decrease almost 50% in the gross production in days with very high variability respect to the production in days with low variability. This difference is clearly reduced when the plant use a TES system.

TABLE 2. Decrease in the gross production of a CSP plant with and without thermal storage as a function of the variability of the solar radiation.

Level of variability	Decrease in gross production (%) PTP0	Decrease in gross production (%) PTP7.5
Medium	15	3
High	33	4
Very high	47	6

In Fig 3 we present the DNI and the GP_d produced by the PT plant without thermal storage with the synthetic sets with low (a), medium (b), high (c), and very high (d) variability for the day of the year 174. In Fig 4 we present the same data but for the PTP7.5 (PT plant with thermal storage).

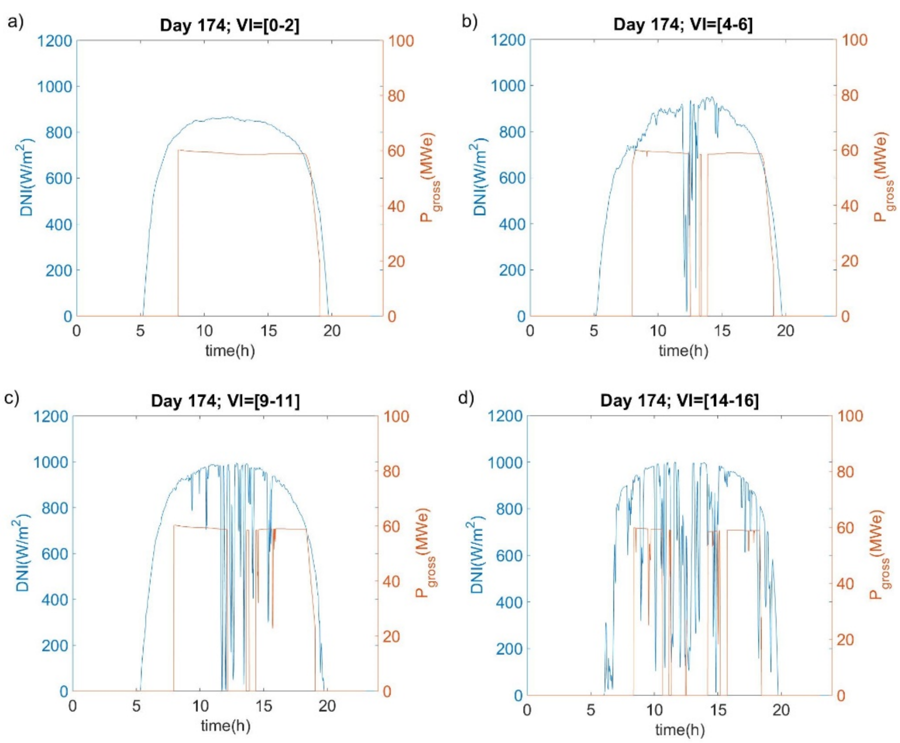

FIGURE 3. Gross power produced by the PT plant without TES and synthetic DNI for the day 174 with low (a), medium (b), high (c), and very high (d) variability.

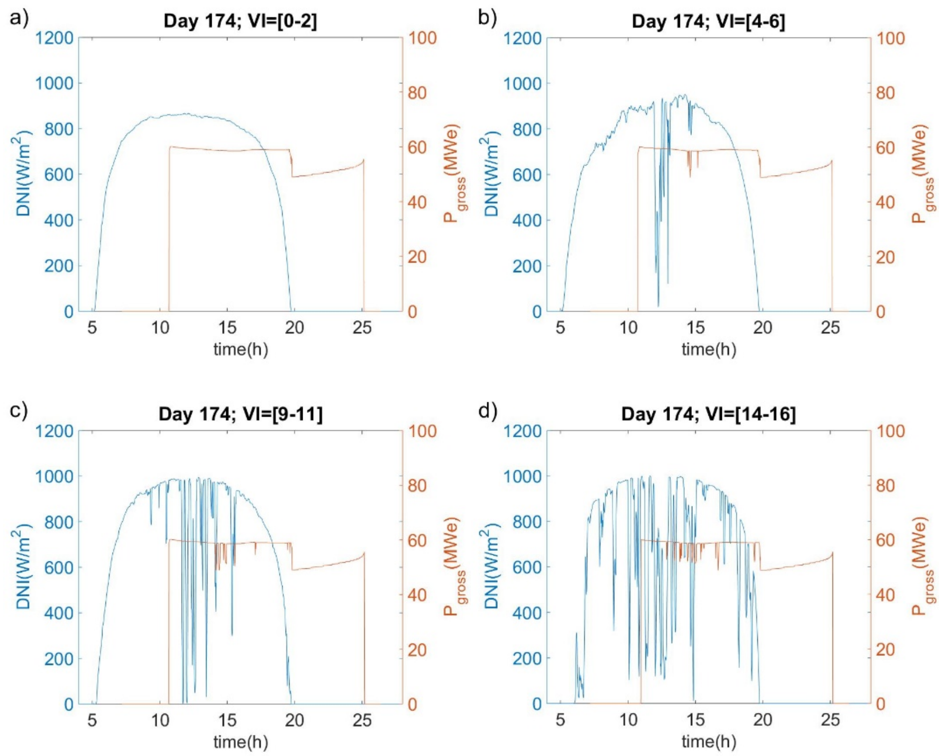

FIGURE 4. Gross power produced by the PT plant with TES and synthetic DNI for the day 174 with low (a), medium (b), high (c), and very high (d) variability.

From Figure 3 it can be observed that the cloud transients have a significant impact on plant production when there is no storage system to damp this effect increasing the number of turbine stops and start-up situations and reducing the collected solar energy. In the case of the plant with thermal storage, even in the high and very-high variability scenarios (Figure 4-, c and d) the turbine does not stop and the system works most of the time at nominal conditions.

SUMMARY AND CONCLUSIONS

In this research work, we quantify the impact of the intra-daily variability of the solar radiation in the production of a PT plant with and without thermal storage. To that end, we generate four synthetic complete annual sets of DNI in the 1-min resolution for the location of Seville with similar features as the measured data in terms of energy and distribution but with different levels of variability.

We observe that the decrease in the gross production can reach a 47% in the case of the dataset with very high variability and the plant without thermal storage. This difference is reduced to a 6% when having a thermal energy storage system.

The TES reduces the impact of the variability of the solar radiation on the production of a PT plant decreasing the number of turbine stops and start-up situations.

REFERENCES

1. Larrañeta M., Fernandez-Peruchena C., Silva-Pérez M., Lillo-Bravo I, 2018. Methodology to synthetically downscale DNI time series from 1-h to 1-min temporal resolution with geographic flexibility. Solar Energy, 132, 573-584.

2. Migliari L., Arena S., Puddu P., Cocco D, 2016. Thermo-fluid Dynamic Analysis of a CSP Solar Field Line During Transient Operation. Energy Procedia 101, 1167-1174.
3. Almasabi A., Alobaidli A., Zhang T. J., 2015. Transient Characterization of Multiple Parabolic Trough Collector Loops in a 100 MW CSP Plant for Solar Energy Harvesting. Energy Procedia 69, 24-33.
4. Noureldin K., Hirsch T., Pitz-Paal R, 2017. Virtual Solar Field - Validation of a detailed transient simulation tool for line focus STE fields with single phase heat transfer fluid. Solar Energy 146, 131-140.
5. Moreno-Tejera S., Silva-Pérez M. A., Ramírez L., Lillo-Bravo I., 2018. Evaluation of classification methods according to solar radiation features from the viewpoint of the production of parabolic trough CSP plants Renewable Energy, 121, 429-440.
6. Rohani, S., Fluri, T., Dinter, F., 2016. Modelling, Simulation and Data Validation of a Solar Thermal Parabolic Trough Plant with Storage. Conf. Proc. SolarPaCES 2015.
7. Stoffel T., Renne D., Myers D., Wilcox S., Sengupta M., George R. et al. Best Practices Handbook for the collection and Use of Solar Resource Data. National Renewable Energy Laboratory, 2010.
8. Fernández-Peruchena C., Vignola F., Gastón M., Lara-Fanego V., Ramírez L. et al., 2018. Probabilistic assessment of concentrated solar power plants yield: The EVA methodology. Renewable and Sustainable Energy Reviews, 91, 802-811.
9. S. Moreno-Tejera, M. A. Silva-Pérez, L. Ramírez, I. Lillo-Bravo, 2017. Classification of days according to DNI profiles using clustering techniques. Solar Energy, 146, 319–333.