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Validation of Solar Extinction Model at Plataforma Solar de Almería

SolarPACES

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Abstract. Solar extinction should be one of the most important factors to select the best locations for solar tower plants. The optical path between the heliostats and the receiver (slant range, SR) very often exceed 1 km. This distance could involve many particles in the atmosphere, which absorb and scatter the reflected solar radiation. Therefore, it is necessary to know the radiative losses due to solar extinction at the location and to have models rigurously validated with experimental data. At PSA there is a database with more than 6 years of solar extinction measurements. These data have been obtained thanks to a solar extinction measurement system developed by The Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT). This database allowed the development of a Typical Solar Extinction Year (TSEY). This TSEY presented an average annual solar extinction value of 6 ± 2 % for a measurement distance of 741.63 m. With this amount of data a model to estimate solar extinction has been validated at PSA. The input data used were the aerosol optical depth (AOD) and the SR. For this purpose, average daily extinction values were estimated with a model. From this new simulated database, a synthetic TSEY was developed in order to compare it with the experimental TSEY. In both cases, the average annual solar extinction values were in agreement with the value of 6 ± 2 % (741.63 m). By this way, the model has been validated and it could be used to estimate solar extinction worldwide.

Keywords: CSP, Thermoelectric Solar Tower Plants, Solar Extinction, Typical Solar Extinction Year, Model Validation

1. Introduction

The energetic demand of the planet is growing every day. This problem is promoting a drastic change in the methods used to generate electricity. Climate Summits such as Dubai 2023 have highlighted the need to replace fossil fuels with other less polluting energy sources. Among the possible solutions are renewable energies, because they are free of emissions and they are inexhaustible sources of energy. In this context, concentrated solar power (CSP) is presented as a feasible alternative to replace fossil fuels with renewable generation systems. One of the major advantages of this tecnology is the possibility of electricity production during the night [1]. This is not possible with other renewable tecnologies such as photovoltaic systems.

Among CSP technologies, thermoelectric solar tower plants are one of the most feasible options to solve this problem [2]. This technology is based on a group of heliostats located around a large tower. Heliostats are oriented according to sun position and they concentrate the direct solar radiation in a receiver located on the top of the tower. However, thermoelectric solar tower plants have some drawbacks. In many cases, the distance between heliostats and the receiver can be very long, even 1 km or more [3]. This implies a large amount of particles in the optical path between the heliostat and the receiver. These particles absorb and scatter solar radiation, knowing this phenomenon as solar extinction. This parameter is hightly negative for these plants on account of radiative losses could be very high. Also, thermoelectric solar tower plants are usually located in arid zones due to the high direct irradiation. In these zones the dust episodes and the presence of aerosols are common, so it is important to know the extinction levels.

In recent years, major advances have been made in the study of solar extinction [4,5]. The first advances in this topic were the development of models estimating solar extinction in rural atmospheres. However, some authors realized that solar extinction was a local parameter due to it depended on factors such as relative humidity (RH) or particle concentration. Polo et al [6] developed a model to estimate solar extinction with local parameters. For this purpose, a radiative transfer code was used to estimate solar extinction, which allowed the introduction of local parameters such as AOD (Aerosol Optical Depth). AOD is one of the best estimators of extinction, and indicates the aerosol level in the atmosphere. It is defined as the integration of the extinction coefficient from the ground to the atmospheric boundary layer.

In addition to developing models to estimate solar extinction, it is necessary to have measurements to validate them. A solar extinction measurement system was developed at PSA by CIEMAT, and it has been operating daily for more than 6 years [7,8]. This system consists in two digital cameras and a Lambertian target and it is measuring solar extinction for a distance of 741.63 m. With these data a Typical Solar Extinction Year (TSEY) has been developed at PSA for the measurement distance (741.63 m). A typical year is a selection of the most representative months of a total dataset. The development of a typical year requires more than 5 years of measurements, so at PSA this objetive was achieved.

In this work, the model developed by Polo et al [6] has been rigorously validated with the TSEY elaborated by Simal et al [9]. For this purpose, AOD values have been required as input data. These data has been obtained from satellite and from Aerosol Robotic Network (AERONET) station at PSA. Once this objective is achieved, it will be possible to estimate solar extinction worldwide. It would allow the selection of optimal locations for thermoelectric solar tower plants and take better advantage of this technology.

2. Materials and methods

2.1 Description of the solar extinction measurement system

A solar extinction measurement system based on two digital cameras and a Lambertian target has been developed at PSA by CIEMAT. Both cameras have a resolution of 16 bits and are strategically located at (741.63±0.01) m from each other. The Lambertian target is (82.88±0.01) m from the first camera and (824.51±0.01) m from the second one. Figure 1 shows an schematic of the measurement system.

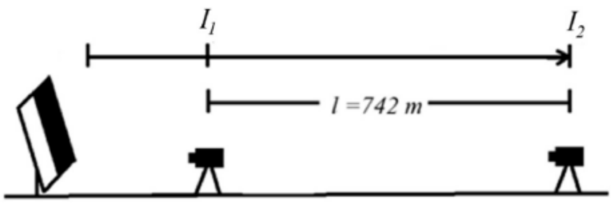

Figure 1. *Solar extinction measurement system at PSA*

This system is operating daily since June 28, 2017, so there are more than 6 years of data. Therefore, it is a robust and viable system, with an absolute measurement accuracy of ± 2%. The system is measuring solar extinction in the bandwith 400-1000 nm. The two digital cameras capture simultaneous images of the target, which presents a diffuse surface of solar radiation. It is possible to calculate the solar extinction from these images. In the paper elaborated by Ballestrín et al [4] the measurement system is perfectly detailed.

2.2 Database processing

Modeling solar extinction requires knowledge of local atmospheric conditions, due to it is a local parameter. The presence of particles in the atmosphere is an important factor, so AOD is an essential parameter to estimate solar extinction. AOD can be parameterized at all wavelengths using Eq. (1).

$$AOD_\lambda = \beta\lambda^{-\alpha} \tag{1}$$

being λ the wavelength, β turbidity coefficient and α Ångström coefficient. β and α coefficients are known as Ångström parameters. For this work, AOD at 550 nm has been used for being the most representative. Average daily AOD values at 550 nm have been obtained from June 28, 2017 to July 20, 2023. This information was downloaded from the "Tabernas_PSA-DLR" station of AERONET. In addition to the information provided by AERONET, AOD satellite data have been obtained. Specifically, data were obtained from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) model and the Moderate Resolution Image Spectroradiometer (MODIS). The spectroradiometer is located on Aqua and Terra satellites. Satellite data for PSA have been obtained for the area between the coordinates (-2.369, 37.081; -2.351, 37.1).

All satellite data have been downloaded from a website promoted by National Aeronautics and Space Administration (NASA) (https://giovanni.gsfc.nasa.gov/). In this website daily AOD data at 550 nm are available. However, AERONET stations did not provide AOD at this wavelength. The "Tabernas_PSA-DLR" station has AOD measurements at 8 wavelengths (1640 nm, 1020 nm, 870 nm, 675 nm, 500 nm, 440 nm, 380 nm and 340 nm). Among these wavelengths, a potential regression was performed to obtain daily Ångström parameters. Using Eq. (1), it was possible to calculate AOD at 550 nm for each day of the database.

Four databases of AOD at 550 nm have been obtained, one for each AOD information source. These databases were filtered, because AOD data at 550 nm were not kept for days with no experimental solar extinction measurements. Finally, 596 daily AOD data at 550 nm were obtained from the AERONET station, 1035 daily values from MERRA-2 model, 746 daily data from the MODIS spectroradiometer (Aqua satellite) and 814 from the Terra satellite. These daily AOD data at 550 nm were used to estimate solar extinction for each day.

2.3 Model's description

The model developed by Polo et al [6] estimates the solar extinction from an equation of third degree (Eq. (2)).

$$Ext(\%) = d_3 SR^3 + d_2 SR^2 + d_1 SR + d_0$$

$$\begin{cases} d_3 = 3.13\,AOD^3 - 1.96\,AOD^2 + 1.60\,AOD - 0.133 \\ d_2 = -14.74\,AOD^3 + 2.49\,AOD^2 - 11.85\,AOD + 0.544 \\ d_1 = 28.32\,AOD^3 - 7.57\,AOD^2 + 48.74\,AOD + 0.371 \\ d_0 = -2.61\,AOD^3 + 3.70\,AOD^2 - 2.64\,AOD + 0.179 \end{cases} \quad (2)$$

being SR the optical path between the heliostat and the receiver; and d_0, d_1, d_2 and d_3 are the coefficients that depend on AOD at 550 nm value entered. It has been used a SR of 742 m, the distance between the cameras of the measurement system. Each coefficient is multiplied by a factor, which have been obtained with Eq. (3).

$$f = \begin{cases} 2.874e^{-3.059\,AOD} - 7.445e^{-114.7\,AOD} & AOD \leq 0.05 \\ 2.358e^{-7.094\,AOD} - 0.836e^{-0.141\,AOD} & AOD > 0.05 \end{cases} \quad (3)$$

2.4 Generation of a TSEY from simulated solar extinction data

Four databases of solar extinction values were obtained with the model as explained in the previous section. Various TSEY have been developed with these databases, 4 cases in total. It has been elaborated a different database depending on the source of information of AOD data at 550 nm, including AERONET, MERRA-2, MODIS (Aqua satellite) and MODIS (Terra satellite). The mean annual solar extinction of these synthetic TSEY was compared with the characteristic mean annual solar extinction at PSA (6 ± 2 %). This data has been obtained from an experimental TSEY elaborated by Simal et al, for a distance of 741.63 m [9]. This experimental TSEY was developed with the measurement database from June 28, 2017 to July 20, 2023.

Typical years have been elaborated following Sandia's methodology, with a concatenation of the most representative months from the databases. The selection was based on Filkenstein-Schafer algorithm (Eq. (4)).

$$FS_{Ext}(y,m) = \frac{1}{N}\sum_{i=1}^{N}\left|CDF_m(Ext_i) - CDF_{y,m}(Ext_i)\right| \quad (4)$$

where CDF_m is the cumulative distribution function of daily values of a month m, $CDF_{y,m}$ is the cumulative distribution function of daily values for a month m and a year y, and N is the number of intervals of both functions. Therefore, TSEY is delivered here in daily basis.

3. Results

Table 1 shows the average annual solar extinction according to the information source selected to obtain AOD data at 550 nm. The values in the table were obtained from the TSEY elaborated for each case. In addition to the average annual, this table shows the maximum and minimum values of each TSEY, the number of days that these TSEY have and the distance used for the solar extinction simulations.

Table 1. *TSEY elaborated using Polo et al model vs Experimental TSEY from PSA*

	Polo et al. Model				CIEMAT System
	AERONET	MERRA-2	MODIS (Aqua)	MODIS (Terra)	
Average annual value	6 ± 2 %	7 ± 2 %	7 ± 2 %	7 ± 2 %	6 ± 2 %
Maximum value	14%	13%	15%	14%	13%
Minimum value	2%	3%	2%	2%	2%
Sample	139	188	153	165	193
Distance	741.63m				

The table shows that the best estimation using the model were obtained with AERONET database, which provides more reliable AOD values. This average annual is in agreement with the average annual of the experimental TSEY. About other statistical parameters, maximum and minimum data have similar values to each other. A distance of 741.63 m has been used for the simulations. This is the same distance used by the measurement system. The TSEY elaborated with data from AERONET station presents an average annual extinction coefficient of (0.083 ± 0.029) km^{-1} and a Visual Range of 47 km (- 12 km, +23 km) [9]. These data are in agreement with the experimental TSEY, because both present the same average annual solar extinction value.

This coefficient can be used to obtain the mean annual solar extinction for any distance, applying Eq. (5).

$$Ext(\%) = 100\left(1 - e^{-k\,SR}\right) \tag{5}$$

being k the average annual extinction coefficient and SR is the optical path in km. Figure 2 shows the average daily of the TSEY from AERONET database. This TSEY consists of 139 days, enough to validate the model.

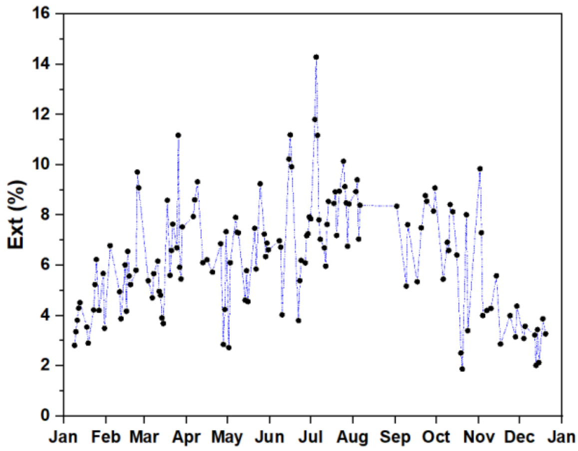

Figure 2. *Simulated TSEY at PSA (2017-2023). AOD inputs obtained from AERONET*

Figure 2 shows the trend of solar extinction over the year. The first months show minimum values, although dust episodes are frequent in February. The extinction level is increasing until the summer season, when solar extinction has maximum values. There are more particles in the atmosphere during this season. There is a higher temperature gradient between the ground and the atmosphere, which favors convective movement and the release of aerosols from the ground. In the following months the solar extinction value decreases. The reason is that in autumn and winter the relative humidity is higher and there is less aerosol release.

4. Conclusions

One of the most important causes of radiative losses in a thermoelectric solar tower plant is the solar extinction. The distance between the heliostats and the receiver is usually very large, even 1 km or more. These distances, along with AOD, are the most significant factors in solar extinction modeling. AOD presents a direct correlation with the presence of particles in the atmosphere whose value increases with long distances. Polo et al [6] developed a local model to estimate solar extinction considering the importance of the local parameters.

A solar extinction measurement system developed by CIEMAT has been operating at PSA for more than 6 years, providing a consistent and reliable measurement database. This has allowed the validation of Polo et al model. Average daily AOD data at 550 nm and a SR of 741.63 m have been used as inputs of the model. AOD at 550 nm was obtained from AERONET station at PSA, and from satellite data, including MERRA-2, MODIS (Aqua satellite) and MODIS (Terra satellite). Therefore, four cases were used, depending on the source of information of AOD.

For each case, a TSEY was generated using simulated values. The best estimation has been obtained using AOD at 550 nm from the AERONET Station at PSA. This simulated TSEY has an average annual solar extinction of 6 ± 2 % for the measurement distance (741.63 m). This TSEY presents an average annual extinction coefficient of (0.083 ± 0.029) km-1 and a VR of 47 km (- 12 km, +23 km). The experimental TSEY elaborated by Simal et al [9] presents the same average annual solar extinction value. With this comparison the model has been rigurously validated. It has also been shown that AOD data at 550 nm from the AERONET station are the best to estimate solar extinction values. The rest of the TSEY show an average annual solar extinction of 7 ± 2 % for the measurement distance (741.63 m). This TSEY have been elaborated with AOD at 550 nm from other information sources (MERRA-2, MODIS (Aqua satellite) and MODIS (Terra satellite)). These results are in the same range as the experimental data, 6 ± 2 % for the measurement distance (741.63 m).

Author contributions

Noelia Simal: Conceptualization, Investigation, Resources, Supervision, Visualization, Writing – original draft; **Jesús Ballestrín**: Conceptualization, Investigation, Project administration, Resources, Supervision, Visualization, Draft review & editing; **Mª Elena Carra**: Conceptualization, Investigation, Resources, Supervision, Visualization, Draft review; **Jesús Polo**: Conceptualization, Investigation, Resources, Supervision, Visualization, Draft review; **Aitor Marzo**: Conceptualization, Investigation, Resources, Supervision, Visualization, Draft review.

Competing interests

The authors declare that they have no competing interests.

Data availability statement

Data will be made available on request

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