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Modelling Atmospheric Attenuation at Different AOD Time-scales in Yield Performance of Solar Tower Plants

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Abstract. Optical losses in central receiver systems may be enhanced by the atmospheric attenuation taking place along the optical path between the heliostat mirrors and the receiver. Ray-tracing and performance codes usually estimate the atmospheric attenuation by a third order polynomial whose coefficients can be input by the user in the model. A sensitivity study on the time-resolution for modelling the atmospheric attenuation is presented in this work by modelling two reference solar tower plants (Ivanpah 1 and Crescent Dunes) with the System Advisor Model (SAM). The input for the atmospheric attenuation has been computed from daily, monthly means and annual mean aerosol optical depth for the Tamanrasset site. The impact of considering one unique polynomial for the whole year to one polynomial every day is higher in the case of Crescent Dunes due to its larger solar field, and relative averages differences in the daily output power may be from around 2% to 4.5% due to the daily peaks of AOD that result in eventual high attenuating conditions for the solar field.

INTRODUCTION

Solar tower plant technology is gaining interest because of its ability to reach higher temperatures that allows for higher efficiency in the steam cycle and attractive use of thermal energy storage. The solar field consists of thousands or even several tens of thousands, depending on the power of the plant, of heliostats around the central tower. The heliostat field optical efficiency is affected by losses of different nature: cosine loss, shadowing, blocking, spillage and atmospheric attenuation. For large solar tower plants the distance between far heliostats and the receiver can be large enough for a noticeable reduction in the optical efficiency due to the atmospheric attenuation. Atmospheric attenuation depends on both the distance that reflected irradiance must traverse (slant path) and on the turbidity characteristics (mainly due to aerosol extinction and water vapor absorption) of the atmospheric layer between heliostat and the tower top. This phenomenon was formerly studied in the late seventies and eighties but the recent increase in solar tower plant deployment has brought a high interest in accurate knowledge and modelling the optical losses caused by atmospheric attenuation. In consequence, remarkable efforts are found in recent literature for both measuring and modelling the local extinction according to the boundary conditions of attenuation in the atmosphere [1–3]. A very recent thorough review on this issue points out that additional effort is still needed to provide accurate and geographically distributed information on extinction data for lowering the costs of solar tower plants [4].

The PRESOL project is intended to further improve the forecasting systems in solar tower plants and it deals in detail with the problem of atmospheric attenuation in both experimental and modeling level. One of the PRESOL

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project activities related to atmospheric attenuation explores the impact that might have to consider the atmospheric attenuation time-dependent instead of static and the impact in modelling a solar tower plant with System Advisor Model (SAM) [5].

MODELLING THE ATMOSPHERIC ATTENUATION

The first equations to compute the atmospheric attenuation in solar tower plants were developed in the late seventies proposing a polynomial function of the slant path based on multiple LOWTRAN calculations [6–8]. Some of these proposed models are implemented in DELSOL and MIRVAL codes for calculation of the solar flux distribution at the receiver [7,9]. This approach is based on a specific polynomial according to two extreme atmospheric states: clear with large visibility atmosphere and hazy conditions with low visibility. In addition, there are other different approaches like the Vant-Hull physical model that includes five explicit physical variables (site elevation, the water vapor density, scattering coefficient, tower height and slant range) [10]. Moreover, the model of Sengupta and Wagner is based on on-site clear sky direct normal irradiance (DNI) ground measurements to estimate the aerosol optical depth (AOD) in the lowest atmospheric layers [4,11,12]. In order to allow the input of AOD to atmospheric attenuation models Polo et al. proposed a polynomial of third order where the coefficients are function of the AOD [2]. This model was developed through multiple radiative transfer calculations performed with libRadtran version 2.0 model [13]. The boundary conditions covered up to 3 km of slant path and a wide range of AOD at 550 nm (0.06-0.72) taken from AERONET stations of target regions of interest in concentrated solar power systems. The model formulation allows to be implemented in ray-tracing codes and yield performance codes as well. The polynomial expression proposed in Polo et al. model is,

$$A(\%) = a\,S^3 + b\,S^2 + c\,S + d \tag{1}$$

where S is the slant range in km, and the coefficients a-d are function of the AOD,

$$\begin{aligned}
a &= 3.13\,AOD^3 - 1.96\,AOD^2 + 1.60\,AOD - 0.133 \\
b &= -14.74\,AOD^3 + 2.49\,AOD^2 - 11.85\,AOD + 0.544 \\
c &= 28.32\,AOD^3 - 7.57\,AOD^2 + 48.74\,AOD + 0.371 \\
d &= -2.61\,AOD^3 + 3.70\,AOD^2 - 2.64\,AOD + 0.179
\end{aligned} \tag{2}$$

Therefore, this approach allows determining a third order polynomial of the slant range, for any attenuating condition represented by the AOD at 550 nm, that may be used in any ray-tracing or yield performance code.

PLANT PERFORMANCE MODELS AND BOUNDARY CONDITIONS

Two large solar power plants in the range of 100 MW have been selected to analyze the sensitivity of yield performance codes to time-scale of atmospheric attenuation. The reference plants correspond to Crescent Dunes for the case of molten-salt heat transfer fluid (HTF) and Ivanpah 1 for the case of water/steam HTF. Table 1 summarizes the main technical characteristics of the reference plant models used.

Input models for each plant have been prepared for System Advisor Model (SAM). SAM is developed and distributed by the National Renewable Energy Laboratory (NREL) as a free software tool for predicting hourly and sub-hourly energy production of different renewable energy systems [14]. The specific modules of SAM for modelling direct steam and molten salt power tower have been used in this work [15]. Meteorological input for modeling yield performance has been prepared in the form of Typical Meteorological Year (TMY3) with Meteonorm 7.0 [16]. The site selected for this analysis is Tamanrasset. Annual DNI of the Tamanrasset TMY is 2812 kWh m-2.

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TABLE 1. Summary of the main characteristic of Ivanpah 1 and Crescent Dunes plants

Parameter	Ivanpah 1	Crescent Dunes
Block Power (MWe)	126	110
HTF	Water/Steam	60% $NaNO_3$, 40% KNO_3
Number of heliostats	>50.000	10496
Tower height (m)	140	200
Total reflective area (m^2)	≈800.000	≈ 1.200.000
Maximum distance from tower (m)	1400	1700
Thermal storage capacity (hour)	0	10

Information of aerosols for determining the attenuation polynomial was obtained from MACC reanalysis (http://www.gmes-atmosphere.eu/). Daily values of AOD at 550 nm have been obtained from MACC reanalysis. MACC is a retrieval based on the ECMWF (European Centre for Medium-range Weather Forecast) integrated forecasting system that provides information of many atmospheric compounds in both reanalysis and forecasting modes [17]. The variability of AOD at different time-scales (annual mean, monthly means and daily values) is shown for year 2012 in Figure 1.

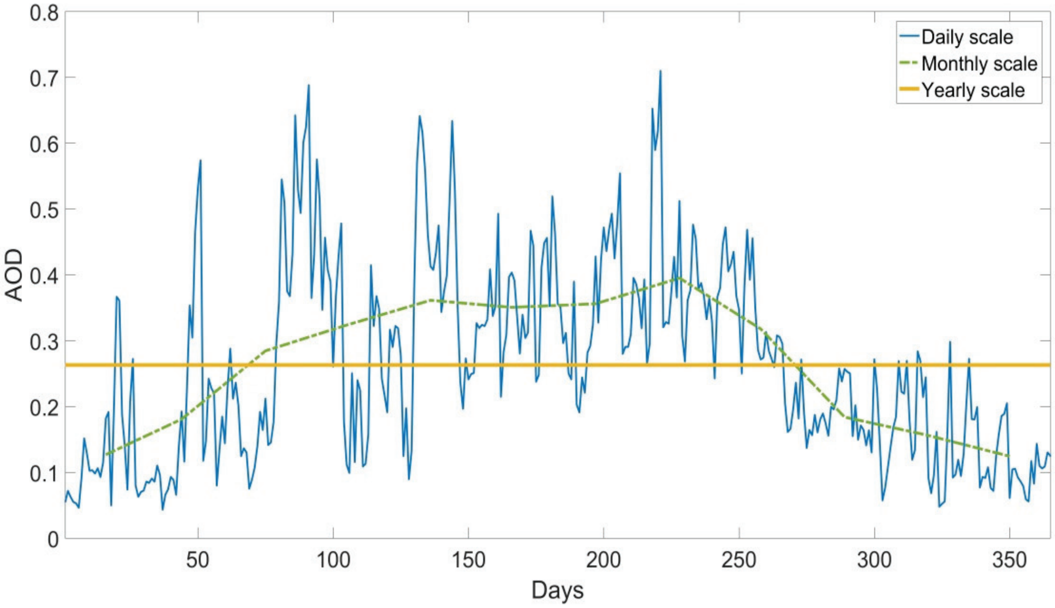

FIGURE 1. Comparison of AOD at different time-scales in Tamanrasset for year 2012 from MACC reanalysis dataset.

Figure 1 shows significant deviations from the annual mean in the monthly means and particularly in daily values of AOD. Since the atmospheric attenuation expected in a solar tower plant must be correlated with the aerosol load (AOD) the assumption of a single mean value of AOD for the whole year, as it occurs in yield performance models, may be very rough, particularly in desert and arid sites, as the case of Tamanrasset site, where important fluctuations and peaks of AOD can take place along the year.

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RESULTS

Plant performance calculations for Tamanrasset site have been done with SAM model using Ivanpah 1 and Crescent Dunes reference plants using tcsdirect_steam and tcsmolten_salt models, respectively. Both models estimate the atmospheric attenuation using a third order polynomial whose coefficients are specified in the plant model input. However, these coefficients are static and unique for the whole year (TMY) modelled by SAM and thus the yield performance calculation assume a steady atmospheric extinction along the year. The Polo model for attenuation as function of AOD has been used to generate one polynomial (annual mean of AOD), twelve polynomials (monthly means of AOD), and 365 polynomials (daily values of AOD). Multiple SAM runs for each plant have been performed in order simulate a time-dependent atmospheric attenuation, 12 runs and 365 runs for the case of monthly and daily, respectively, and the output was properly managed by concatenated months or days of power output. Figures 1 and 2 show the daily power output as a result of considering different time-scales in the atmospheric attenuation for the Crescent Dunes and Ivanpah 1 plants, respectively.

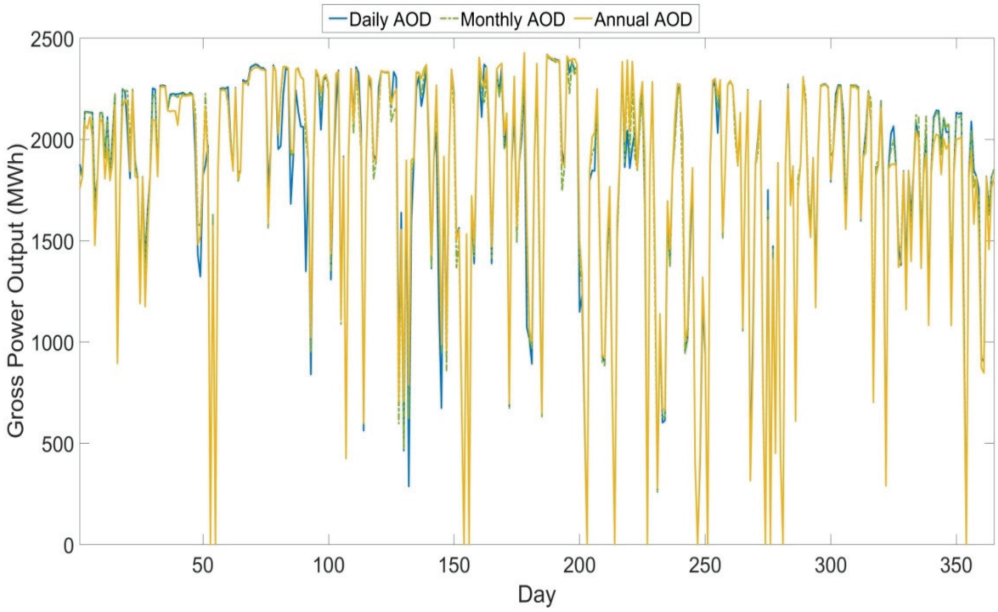

FIGURE 2. Daily power output at different time-scales of atmospheric attenuation in Crescent Dunes plant

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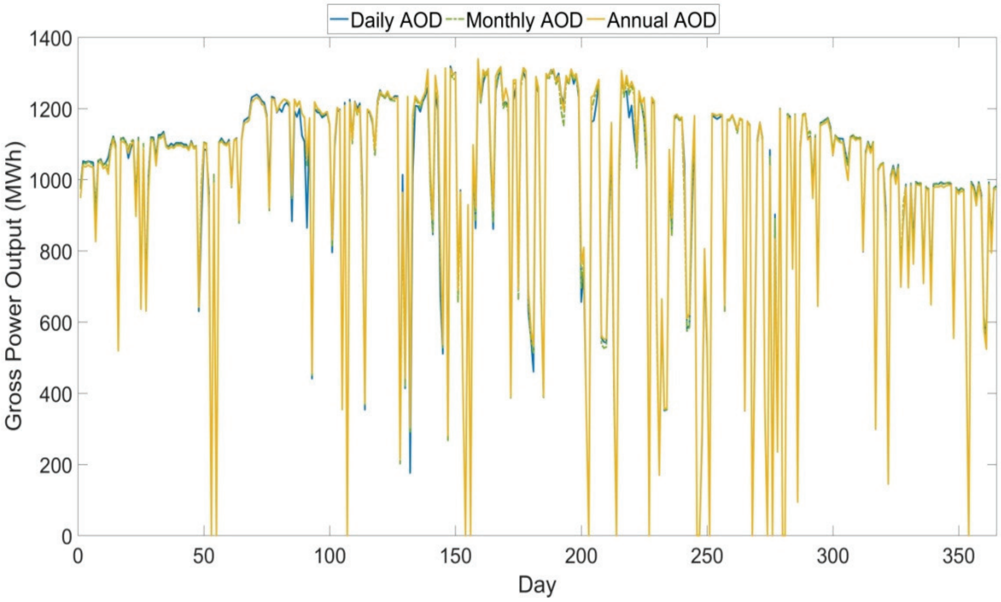

FIGURE 3. Daily power output at different time-scales of atmospheric attenuation in Ivanpah 1 plant

The average differences in assuming a monthly variability of atmospheric attenuation compared to the daily time dependent attenuation were 1.65% and 3.28% of daily power output for Ivanpah 1 and Crescent Dunes, respectively. In the case of assuming a steady state of atmospheric attenuation the average differences in daily power output were 2.36% and 4.66% for Ivanpah 1 and Crescent Dunes, respectively. Table 2 presents the annual gross energy produced for year 2012 by each plant according to the different assumptions for the time-dependent variability of atmospheric attenuation. The results show a higher impact in Crescent Dunes plant to the assumption taken on the time-scale for modelling the atmospheric attenuation due to the larger solar field and maximum distance between heliostats and the receiver.

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TABLE 2. Yield performance (GWh) as a function of time-scale of atmospheric attenuation

Plant	Daily extinction	Monthly Extinction	Annual Extinction
Crescent Dunes	651.07	654.31	654.69
Ivanpah 1	354.99	355.76	356.74

CONCLUSIONS

The study of atmospheric attenuation at both experimental and modelling levels is becoming of high interest with the growth of large solar tower projects. One of the most frequently used ways to model the atmospheric extinction is by a polynomial function of the slant range (the optical path between the heliostat and the receiver), and this is the approach implemented in performance models like SAM. However, performance models are limited to input a specific unique polynomial for extinction according to the atmospheric conditions of visibility (clear to hazy conditions) that is used in a steady state for the whole year. This limitation does not take into account the variability of atmospheric conditions along the year that may result in a time-dependent atmospheric attenuation.

Sensitivity calculations with SAM for Tamanrasset site have been shown the sensitivity of the daily energy output of two typical solar tower plants (direct steam and molten salt) in the range of 100 MW. The sensitivity to the assumptions in the time-scale used for modelling the atmospheric attenuation may result in differences up to 4.5% of the daily power output of the plant when the user input a daily variability of extinction (one different polynomial everyday) compared to the assumption of an annual average extinction using one unique polynomial for the whole year performance calculations. These differences may be much larger in case of eventual high loads of aerosols resulting from dust storms in desert sites or even in Sahara outbreak events in the Mediterranean regions.

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