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Atmospheric Extinction in Simulation Tools for Solar Tower Plants

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Abstract. Atmospheric extinction causes significant radiation losses between the heliostat field and the receiver in a solar tower plants. These losses vary with site and time. State of the art is that in ray-tracing and plant optimization tools, atmospheric extinction is included by choosing between few constant standard atmospheric conditions. Even though some tools allow the consideration of site and time dependent extinction data, such data sets are nearly never available. This paper summarizes and compares the most common model equations implemented in several ray-tracing tools. There are already several methods developed and published to measure extinction on-site. An overview of the existing methods is also given here. Ray-tracing simulations of one exemplary tower plant at the Plataforma Solar de Almería (PSA) are presented to estimate the plant yield deviations between simulations using standard model equations instead of extinction time series. For PSA, the effect of atmospheric extinction accounts for losses between 1.6 and 7 %. This range is caused by considering overload dumping or not. Applying standard clear or hazy model equations instead of extinction time series lead to an underestimation of the annual plant yield at PSA. The discussion of the effect of extinction in tower plants has to include overload dumping. Situations in which overload dumping occurs are mostly connected to high radiation levels and low atmospheric extinction. Therefore it can be recommended that project developers should consider site and time dependent extinction data especially on hazy sites. A reduced uncertainty of the plant yield prediction can significantly reduce costs due to smaller risk margins for financing and EPCs. The generation of extinction data for several locations in form of representative yearly time series or geographical maps should be further elaborated.

INTRODUCTION

Aerosol particles and water vapor cause losses of solar radiation between the heliostat field and the receiver in solar tower plants. This effect, called atmospheric extinction, cannot be neglected and varies significantly with site and time. So far, strong assumptions are usually made to estimate the CSP (concentrated solar power) plant yield reduction due to extinction and either a clear or a hazy atmospheric condition is selected. This might not be sufficiently accurate especially in arid areas which are interesting for CSP. Recently, methods have been developed and validated to determine site and time dependent extinction with on-site measurements ([1], [2]) during resource assessment which is a step forward. This paper summarizes recent methods for the application of extinction data in ray-tracing and plant optimization tools. Further, an overview about existing methods to derive a site- and time-dependent atmospheric extinction is given. We present an example for the effect of different assumptions for extinction on a tower plant by comparing the resulting plant yield with the one obtained with measured extinction data. Furthermore, we discuss remaining open issues and suggestions for future research.

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ATMOSPHERIC EXTINCTION IN SIMULATION TOOLS

A beam of incident light is partly attenuated while traveling through an atmospheric layer and partly transmitted. The exponential Beer-Lambert-Bouguer law describes the monochromatic transmittance ($T_{x,\lambda}$) per traveled distance x with the spectral extinction coefficient $\beta_{ext,\lambda}$ (in m^{-1}).

To approximate the atmospheric extinction, often the meteorological optical range (MOR) is used, describing the visibility. MOR is defined as the length of the path in the atmosphere which is required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a color temperature of 2700 K, to 5 % of its original value ([3], [4]). The Koschmieder approximation ([5]) connects the MOR with $\beta_{ext,550nm}$ and $T_{x,550nm}$, which is the spectral transmittance for the traveled distance through a medium x (path length) at a wavelength of 550 nm:

$$\mathrm{MOR} \approx \frac{-\ln 0.05}{\beta_{ext,550nm}} \approx \frac{3}{\beta_{ext,550nm}} \approx \frac{-3 \cdot x}{\ln(T_{x,550nm})} \tag{1}$$

The Koschmieder approximation neglects the spectral variation of the extinction coefficient. The standard visual range (SVR) is defined in a similar way but with a threshold of 3 % instead of 5 %.

State of the Art: Atmospheric Extinction in Simulation Tools

Usually, constant model equations are applied to describe radiation loss due to atmospheric extinction dependent only on the slant range (distance between heliostat and receiver) in ray-tracing or plant optimization tools. Even though transmittance of solar radiation through a medium is expressed with the exponential Lambert-Beer-Bouguer law, most of the standard model equations are polynomials. Some tools allow the decision between different extinction levels. In the following, a selection of available data sets, models and model equations implemented in the existing tools are presented.

MIRVAL ray-tracing code: Vittitoe and Biggs [6] generated a data set which was calculated by numerical integrations of spectral transmittance data using LOWTRAN 3. The data set was generated for certain distinct conditions and used to generate the Leary and Hankins model equation (L&H model equation, [7]) with the help of a polynomial fit to the data set. The L&H model equation was developed to be included in the MIRVAL code developed by Sandia National Laboratories ([7]) to compare designs of heliostat-receiver optics for central receiver solar power plants. The L&H model equation in MIRVAL describes the atmospheric transmittance with a polynomial of second degree in x. It can be manipulated with the flexible factor ABSORB which can be user defined. In the MIRVAL manual it is mentioned that [6] recommend ABSORB to be 1 for slant ranges up to 1 km, receiver heights 100-300 m and an approximate elevation of 600 m a.m.s.l.. This results in a MOR equal to 27.1 km.

STRAL ray-tracing code: The software tool STRAL ([8]) developed by Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) also offers the option to apply the L&H model equation to simulate the atmospheric extinction (the factor ABSORB is hereby constantly set to 1). For slant ranges of less or equal than 1 km, the relationship of the MIRVAL code is applied, while for larger slant ranges an exponential decrease is used. The transmittance is calculated for each heliostat in one calculation instead of for each ray. In STRAL it is also possible to include a user-defined transmittance versus slant range relation.

SPRAY ray-tracing code: The ray-tracing code SPRAY ([9]) is based on the MIRVAL code and was developed for the evaluation of the optical performance of solar tower plants. SPRAY provides already several options to consider radiation extinction in the power plant due to atmospheric extinction. Options are neglecting atmospheric extinction, the L&H model equation can be applied (slightly modified to assure a transmittance of 1 for a slant range of 0 m) or the STRAL model equation can be used. Also, a hazy condition which is described by the hazy model equation of DELSOL and a user-defined transmittance versus slant range relation are options in SPRAY. Recently, SPRAY was extended with an exponential model equation dependent on the slant range:

$$\mathrm{T}_{x,\mathrm{SPRAY\,exp}} = \exp(-ABSORB \cdot x) \tag{2}$$

where x is given in m. ABSORB can be chosen according to the current atmospheric conditions.

The Pitman and Vant-Hull Model: Pitman and Vant-Hull [10] developed a transmittance model to calculate the extinction of a solar beam propagating between a heliostat and a receiver. The included formulas display functional fits to the data of [6]. The P&V model contains five physical variables: the atmospheric water vapor density, the scattering coefficient at a wavelength of 550 nm, the site elevation, the tower height and the slant range. The possibility to include on-site measurements of meteorological parameters in the P&V model enables a more site specific determination of atmospheric extinction than the previously described static model equations.

The HFLCAL code: The "Heliostat Field Layout CALculation" code HFLCAL ([11]) provides several options to include atmospheric extinction. Atmospheric extinction can be neglected, the standard clear atmosphere as described in STRAL can be assumed (default option in HFLCAL) and also the P&V model (additional input of water vapor density and scattering coefficient) can be applied in addition to a user-defined extinction model. Also, a factor can be introduced to increase or decrease the standard extinction coefficient from STRAL.

The Greenius code: The software Greenius (technical and economical simulations of CSP plants, [12]) is a simulation environment for the calculation and analysis of the annual performance of renewable power projects. The solar field, the receiver geometry and their performance data were generated with HFLCAL. Therefore, atmospheric extinction is included in the same way as in HFLCAL with the standard clear setting.

DELSOL code: DELSOL ([13]) was developed by Sandia National Laboratories to calculate the optical performance and optimal system design for solar thermal central receiver plants. Model equations to determine atmospheric extinction in tower plants for two different scenarios for Barstow, CA, USA have been developed and implemented in DELSOL based on the data set of [6] and the publication of [14]. The model equations for a default clear day and a hazy day can be described with two different cubic equations. The clear case results in 10 % DNI (direct normal irradiance) loss for a slant range of 1 km (broadband transmittance T_{1km}=0.9, corresponds according to the Koschmieder approximation of Eq. 1 to MOR of about 29.3 km) while the hazy case results in 25 % DNI loss (T_{1km}=0.75, MOR of about 10.2 km). Additionally, it is also possible to user-define the extinction level in DELSOL.

The System Advisor Model (SAM): In the model SAM developed by the National Renewable Energy Laboratory (NREL) [15, 16] it is possible to approximate the atmospheric transmittance using a polynomial of third order which is dependent on the slant range. The clear model equation of DELSOL is used in SAM as the default case.

The Model of Ballestrín and Marzo: Ballestrín and Marzo [17] describe spectral transmittance simulations performed with MODTRAN. The simulations have been carried out for a solar power tower plant at sea level during spring/summer in a rural environment. The spectral transmittance (300-2500 nm) for five different slant ranges and for a clear and a hazy day ("visibility" of 23 and 5 km, respectively) have been calculated using the HITRAN molecular spectroscopic data base. The used definition for "visibility" is unclear. As the simulations have been performed with MODTRAN, it can be assumed that "visibility" refers here to the SVR, determined similar as in Eq. 1, but considering a broadband extinction coefficient (β_{ext}). The simulations have been performed for rural standard aerosol and fits through the five slant ranges according to the simulation results determine two cubic model equations. Using the Koschmieder approximation of Eq. 1, a MOR of 20.16 and 5.32 km can be calculated for the clear and hazy model equation, respectively. [17] found discrepancies between the performed simulations and the DELSOL and MIRVAL model equations. [18] point out that the differences of the performed MODTRAN simulations by [17] mainly arise from the different elevations at which the simulations for the model equations were made. The MODTRAN simulations have been conducted for sea level while the DELSOL and MIRVAL model equations were derived using data sets from a location at an elevation of about 610 m a.m.s.l. (Barstow, CA, USA). The MIRVAL code also allows to scale the atmospheric transmittance model with the ABSORB factor according to the local atmospheric conditions. [17] assumed this factor to be equal to 1 as recommended for slant ranges up to 1 km, receiver heights of 100-300 m and an approximate elevation of 600 m a.m.s.l. ([18]). The conclusion of [17] that the basic DELSOL and MIRVAL codes are only valid for specific atmospheric conditions is therefore correct, but as the MODTRAN simulations presented have not been performed for the according conditions the conclusion that there is a physical discrepancy between the DELSOL and MIRVAL codes and the MODRAN simulations is not correct. Additionally, as a reaction to this paper, the comment of [19] discusses the inaccurate spectrum for the spectral integration which is performed in the publication of [17]. Nevertheless, the resulting transmittance model equations of this study are implemented in the Tonatiuh code ray-tracing software ([20]). Tonatiuh is a freely available ray-tracing tool which can be used to design and analyze the optical and energy efficiency of CSP plants ([20]).

The mentioned models and model equations are a selection of the most applied ones and are displayed in Fig. 1. The left graph of Fig. 1 shows the transmittance for June 29, 2013, 12:30 UTC dependent on slant range. The model equations of DELSOL, MIRVAL, STRAL, HFLCAL and the two model equations of [17] are static and not adjustable with time. The exponential model equation of SPRAY is designed in this example to fit best T_{600m} calculated with the Koschmieder approximation (Eq. 1) and the corrected MOR measurements of a FS11 scatterometer of Vaisala for a slant range equal 600 m for June 29, 2013, 12:30 UTC at the Plataforma Solar de Almería (PSA). A detailed description of the corrected MOR data set can be found in [1]. The P&V model is simulated exemplary with additional information from measurements of ambient temperature, barometric pressure and relative humidity. A tower height of 215.48 m is considered. Raw measurements of MOR performed by the FS11 scatterometer are considered and translated into the scattering coefficient applying Eq. 1. In the P&V model neither different solar spectra at different air masses are considered nor different aerosols can be described e.g. via the input of the Ångström exponent.

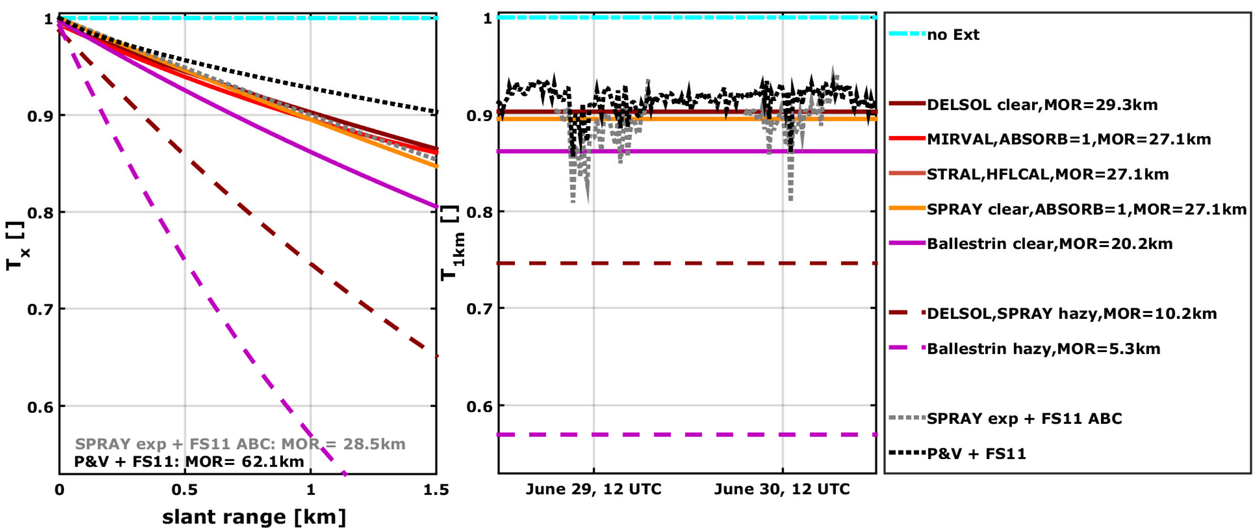

FIGURE 1. Left: Transmittance derived with different exemplary models and model equations for June 29, 2013, 12:30 UTC at PSA, dependent on slant range. Right: Transmittance for a slant range of 1 km from June 29-30, 2013.

It can be seen that the clear DELSOL model equation, the clear SPRAY model equation, the STRAL model equation and the exponential SPRAY model differ for this date less than 0.02 from each other and the MIRVAL model equation for slant ranges above 100 m. The P&V model show a slightly higher transmittance for this date. The clear model equation of [17] is steeper and deviates stronger from the other clear model equations the larger the slant range. The hazy model equations of DELSOL and [17] are even more steep models and result in much lower transmittances for all slant ranges.

The right plot in Fig. 1 also shows the described model equations for a time period between June 29 and 30, 2013 with a temporal resolution of 10 minutes. The curve for the hazy situation implemented in DELSOL as well as in SPRAY is static. That means that they are not adjustable for the current atmospheric condition. The default model equation in MIRVAL, STRAL and HFLCAL as well as the clear model of DELSOL and SPRAY with the factor ABSORB equal 1 are also static model equations. The same accounts for the clear and hazy model equation of [17]. The clear case model equations display a transmittance for a slant range of 1 km (T_{1km}) of around 0.90 (except of the clear model of [17] at 0.86). The DELSOL and SPRAY model equation for a hazy condition displays a constant transmittance of 0.75, the hazy model equation of [17] lies at 0.57. T_{1km} from the adjustable models (the P&V model or the exponential model equation of SPRAY) vary for the exemplary time period with time between 0.81 and 0.95.

The static model equations are not able to represent diurnal, monthly or annual variations which probably occur at every site. At a specific site, T_{1km} of 0.9 might be a suitable value to present the annual mean T_{1km}, but this is certainly not the case for all sites.

Existing Methods to Determine Extinction

To describe the site-dependent variations in atmospheric extinction, the generation of time series is crucial. The already described model of [10] or the exponential model equation of SPRAY can be applied to derive such time series. Anyway, additional measurements of the extinction coefficient or MOR are necessary to apply these models for a certain site and time.

Recently, studies and investigations have been conducted to determine time series of atmospheric extinction in the lowest layer of the atmosphere to enhance solar tower simulations. These studies are summarized in the following.

The **Swaihan experiment of [21]** consisted of pyrheliometers in different distances to a heliostat. Mirror convexity, tracking, DNI and ray-tracing uncertainties and correction factors due to the partly shaded pyrheliometers led to high uncertainties in atmospheric extinction estimation [22].

The **Jebel Hafeet experiment of [21]** consisted of four pyrheliometers located at different elevations between 340 m and 1035 m a.m.s.l. at the Jebel Hafeet Mountain (highest mountain in UAE). The experiment intends to derive the vertical extinction profile from the measurements along the mountain slope. For this specific site, a model to simulate the transmittance of DNI with distance of propagation has been developed.

The **aerosol optical depth (AOD) and boundary layer height (BHL) based simulation approach of [23]** can be used to model atmospheric extinction in a solar tower plant. It is assumed that all present aerosol particles are homogeneously distributed in the boundary layer. The AOD is provided by AERONET, while the BLH can be taken from European Centre for Medium-Range Weather Forecasting (ECMWF). The simulations have been performed for 500 nm and one site in Morocco (Ouarzazate). No validation of the approach with ground measurements has been published so far.

The **digital camera approach [24]** is based on simultaneously taking pictures of a white target from different distances. From the different brightness of the target in the pictures, the extinction coefficient is intended to be determined. The measurement method is still under development and will be set up at PSA.

The **scatterometer approach** with an absorption and broadband correction (ABC) **[1]** enables the determination of atmospheric transmittance of radiation in solar tower plants with the help of surface measurements of the FS11 scatterometer of Vaisala in combination with an ABC software. The ABC software is based on radiative transfer simulations with the software package libRadtran ([25]) and information about on-site ambient temperature, barometric pressure and relative humidity. Optionally additional input of AERONET sun photometer data can be included. The FS11 is based on a monochromatic near-infrared light source emission and measures the strength of scattering processes in a small air volume mainly caused by aerosol particles. The ABC software focuses on the one hand on correcting the FS11 measurement for missing consideration of the broadband absorption. On the other hand it translates the monochromatic measurement of the scatterometer into broadband transmittance as the broadband solar transmittance is of interest for solar resource assessment for CSP. The estimated absolute uncertainty of the ABC corrected FS11 measurements for T_{1km} equal 0.9 (which is a typical value for clear atmospheres) and a 10 minutes temporal resolution is 0.04. For yearly averages, an absolute uncertainty of 0.02 is expected.

Additionally, a **transmissometer approach with ABC correction [1]** uses the ABC correction for measurements with the LPV4 transmissometer of Optec. As the transmissometer emits radiation in center of the solar spectrum, the required ABC correction is smaller than for the FS11. Anyhow, high maintenance demand complicates the application of the LPV4 during CSP resource assessment.

The **P&V model of [10]** can be used in combination with for example scatterometer or transmissometer measurements to derive site- and time-dependent transmittance data. Anyhow, it has to be kept in mind that spectral variations are not included in the model and the used sensor for the derivation of the scatter coefficient has to be chosen carefully.

The **DNI based surface transmittance model ([18], [26] and [27])** is based on on-site clear sky DNI data to estimate the AOD (aerosol optical depth) in the lowest atmospheric layers. In the first version from [18], [26] and [27] extinction between a heliostat and a receiver is estimated only from clear sky DNI. This approach is especially interesting for plant operators due to its only dependence on DNI measurements which are usually available for running CSP plants and also for attractive sites for CSP which are assessed for solar resources. The approach is already implemented in the simulation tool named SoFiA (Solar Field Assessment for Central Receiver Systems) presented by [28] in an adapted version.

The **DNI based model of [2]** describes an enhanced version of the model of [18] which uses DNI and additional temperature, pressure and relative humidity measurements. These additional measurements are usually available at any prospective CSP site. The enhanced version includes the fact that aerosol type as well as the precipitable water vapor vary significantly with site and time and has to be considered accordingly. The estimated uncertainty varies around 0.04 for T_{1km} equal to 0.9 and 1 minute temporal resolution, dependent on the assumed aerosol height profile. So far, the approach is tested only at the clear site of PSA. The approach is based on radiative transfer calculations which have to be performed specifically for the site of interest.

For resource assessment purposes, the presented methods of [21] might not be options due to the high maintenance demand of the setup. The derived data sets of [21] have also not been validated and the same accounts for the methods of [23], [24] and [10]. The method of [24] is still under development.

The scatterometer approach of [1] was compared to the transmissometer approach and showed a mean bias of 0.01 and a RMS of 0.04. Therefore it can be concluded that the FS11 in combination with the ABC software is suited to derive site-dependent atmospheric extinction in solar tower plants due to its low power and maintenance demand especially in harsh environments and remote sites.

The approach of [18] was validated in [2] and it was shown that the site-dependent development of the model is crucial. The enhanced DNI based model of [2] results in a mean bias of about 0.01 to 0.03 (dependent on the assumed aerosol height profile) and a RMS of 0.05 in comparison to a data set generated with the scatterometer approach of [1].

Therefore, it can be recommended to roughly identify if a site is rather clear or hazy with the usage of the enhanced model approach of [2]. To examine the atmospheric extinction on hazy sites in detail, the approach of [1] based on the FS11 scatterometer is suggested.

POWER PLANT SIMULATIONS

Ray-Tracing Simulations

The aim of the performed ray-tracing simulations was to reveal miscalculations in the plant yield estimation if only standard model equations are applied instead of measured extinction time series. One exemplary plant at the site of PSA was chosen for several ray-tracing simulations with the ray-tracing tool SPRAY ([9]). The chosen plant was adapted of another study dealing with the sunshape effect on tower plants ([29]) and has a design thermal power of 162 MW_{th} (71.1 MW_{th} maximum power that can be used by the power block, 27 MW_{el} assuming a power block efficiency of 0.38 after [30]) with a cavity molten salt receiver. The heliostat field geometry is shown in Fig. 2 (left). A transmittance time series for PSA according to the approach presented in [1] was used to perform power plant simulations for the first time with temporal flexible transmittance data. One complete year (May 22, 2013 until May 21, 2014) has been processed as the effect of the atmospheric extinction and DNI have an annual course.

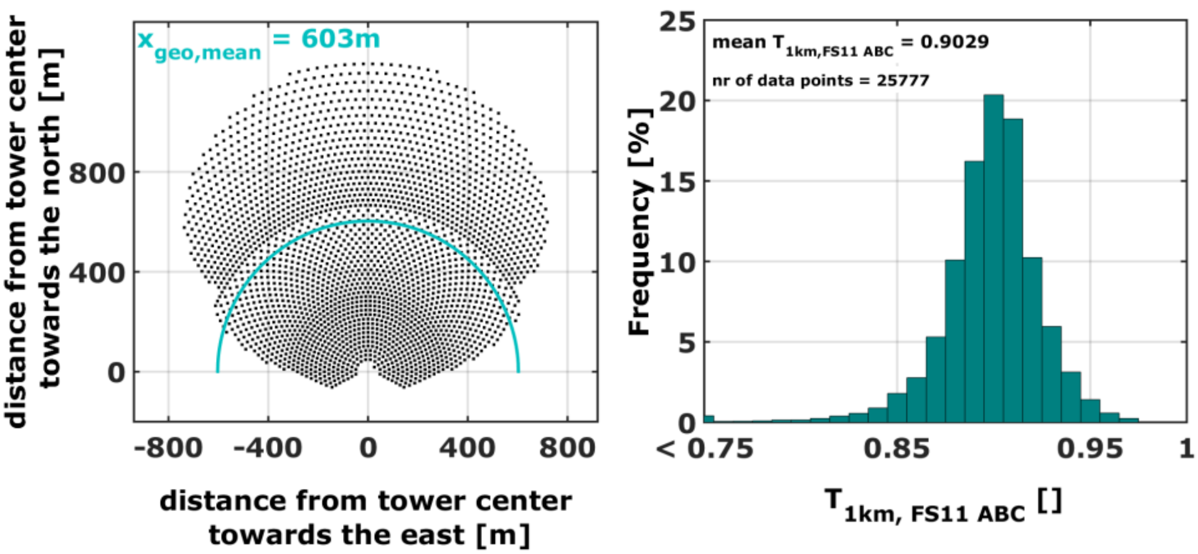

FIGURE 2. Left: Heliostat field of [29] for PSA with indication of the average slant range $x_{geo,mean}$. Right: T_{1km} frequency distribution of the used time series for PSA performed with the method of [1] from May 22, 2013 to May 21, 2014.

Various simulations have been performed with different transmittance model equations and are compared to the results obtained with the measured data set.

Extinction input: To evaluate the importance of on-site atmospheric extinction measurements, four different scenarios have been simulated. In the first scenario atmospheric extinction is completely neglected. In two of the scenarios standard transmittance model equations have been applied which can be considered as state of the art: The clear model equation of SPRAY and the hazy model equation of DELSOL. In the fourth scenario, a time series of extinction measurement performed at PSA according to the scatterometer approach of [1] has been used as input. The mean T_{1km} for the examined time period is about 0.9 at PSA (see Fig. 2, right). The mean transmittance at PSA is therefore close to that of the clear models from SPRAY and DELSOL. The same DNI measurements from PSA have been used in all four simulations. Comparing the results with the simulations which use the standard clear model equation with ABSORB equal 1 or the hazy model equation highlight how large the errors in yield calculations can be if no site and time-dependent transmittance series are included but only standard transmittance assumptions.

Operation strategy: Two different overload dumping scenarios have been investigated. Overload dumping can be understood as defocusing of heliostats to prevent overload of the maximal receiver as well as storage capacity. In one scenario no overload dumping is performed. In the other presented scenario, overload dumping due to the receiver and storage limitations is regarded. In this scenario, overload dumping occurs if the net thermal power available at the receiver to be transferred to the heat transfer fluid exceed the receiver design power more than 15 % and a finite storage capacity of 853 MW_{th} (corresponds to 12 hours of storage of the maximum power used by the power block (71.1 MW_{th}) with an efficiency of 0.95 as in [31]) is assumed. Therefore, a strict example for overload dumping is considered.

No operation is assumed if the thermal power transferred to the molten salt is less than 15.5 MW_{th} which corresponds to about 22 % of the design thermal power. Data points with DNI of less than 150 Wm^{-2} and solar zenith angles larger than 89° are not considered due to underload dumping effects.

Results of Simulations

The ray-tracing simulations showed that if no overload dumping is considered, the effect of atmospheric extinction accounts for a loss of about 7.04 % of the annual plant yield (see Fig. 3). Considering overload dumping due to the receiver and the storage limitations reduces the effect to about 1.56 %. It should be noted that the receiver maximum load has been selected conservatively. The application of a quite low receiver maximum load causes the high overload dumping so that a wide range of dumping conditions is covered by the study. Applying the standard clear extinction model equation of SPRAY instead of the variable extinction time series would result in an underestimation of the annual plant yield of about -0.38 % at PSA. If overload dumping is allowed, the effect accounts for about -0.16 %. The application of the hazy model equation results in annual yield underestimations between -11.18 % and -3.66 % for the two overload dumping scenarios. This can be well explained as overload dumping occurs during clear and undisturbed time periods which are characterized by high DNI values. These time periods are usually also connected to a low aerosol and water vapor load in the lower boundary layer which means also low extinction levels. Therefore, overload dumping occurs more often in periods for which the clear standard model equation underestimates the plant yield than in periods during which the standard model fits well to the real conditions.

Overload dumping due to the receiver and storage limitations accounts for up to 17.5 % of the annual heat delivered to the power block in the case in which the clear SPRAY model equation is considered while it is decreased to 8.5 % if the hazy model equation of DELSOL describes atmospheric extinction. The high rate of overload dumping stresses the importance of the consideration of site-specific DNI as well as transmittance conditions during the plant optimization. The simulated plant was designed for a design year with 4.2 % lower DNI levels than during the here investigated time period ([29]). For a complete discussion of the effect of atmospheric extinction, overload dumping has to be therefore included in the discussion to fully understand the effect.

The calculated results for the effect of atmospheric extinction in the exemplary tower plant for PSA are compared to different studies from the literature ([32]-[39]). For all presented studies, no site specific time series of extinction was considered and no information is given if overload dumping is included in the studies. Within the limitations of the comparison due to the missing information in the studies, the results for the atmospheric extinction effect in solar tower plants lie in the same range as in the investigations of this work. Recently, [39] investigated the sensitivity of solar plant production for modelled atmospheric extinction. They modelled atmospheric extinction with the help of AOD measurements. Unfortunately, the presented ray-tracing calculations for two different power plants have only been performed for two static AOD levels (0.1 and 0.7), instead of various AOD levels which would be necessary for a sensitivity analysis. Also in this study no information is given about the overload dumping strategy.

The effect of atmospheric extinction at PSA is more pronounced during winter than during summer due to overload dumping. This is an interesting finding, as the extinction levels are higher in summer. Applying the standard clear model equation of SPRAY instead of the measurement time series for PSA results in an underestimation of the daily yield which is stronger in the winter months than during summer. The DNI reaches higher values in winter due to the shorter distance of the Earth to the sun and due to the clearer atmosphere. The standard hazy model equation of DELSOL significantly underestimates the plant yield during the whole year.

For higher mean transmittances and MOR at a certain site, also higher plant yields can be expected. While the relationship between the transmittance at 1 km slant range and the thermal power loss has a nearly linear character, the MOR is approximately exponentially connected to the thermal power loss.

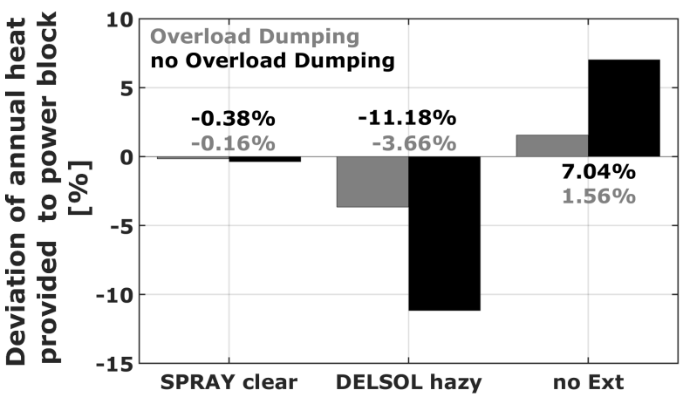

FIGURE 3. Annual effect of atmospheric extinction on the exemplary solar tower plant at PSA. Relative deviation of the annual sum of the heat that is provided to the power block determined with the standard clear model equation of SPRAY, the hazy model equation of DELSOL and neglecting the atmospheric extinction compared to the results of calculating with the exponential approach of SPRAY and the transmittance time series for PSA. Results are shown before overload dumping (black) and after the complete overload dumping (grey).

CONCLUSION AND FUTURE RESEARCH NEEDS

To conclude, considering on-site atmospheric extinction time series instead of standard conditions enhances the accuracy of the calculation of the annual course and the plant yield. Therefore, it is recommended to include atmospheric extinction data sets especially in regions with an expected high or very low aerosol and water vapor load during resource assessment. [1] and [2] provide methods to produce such time series. At clear sites like PSA, standard assumptions might be sufficiently accurate to estimate the average effect of atmospheric extinction in tower plants. To identify a site as clear, the method based only on DNI measurements presented in [2] can be recommended. The detailed examination of extinction at hazy sites can be performed with the scatterometer method of [1].

In the frame of the 2nd DNICast (http://www.dnicast-project.net/) end-user workshop in December 2015, future research needs and options, as well as priorities have been defined to facilitate the generation of extinction data for CSP solar resource assessment. To consider the effect of atmospheric extinction in solar resource assessment for a certain site, representative climatological means of transmittance or data of one representative year for several locations are desired to assess the importance of extinction variability. Also, a geographical map of extinction is of interest. To generate these data sets, information about the aerosol optical depth, aerosol optical properties, aerosol profiles and/or MOR measurement data have to be available. Networks like AERONET or EARLINET, the LIVAS data base and aerosol models or satellite data could provide the required information.

Most of these sources assume the lowermost part of the atmosphere as well mixed while experience at PSA shows sometimes strong small scale variations due to dust plumes and air pollution from the surroundings. So additionally the use of a LIDAR or MAX DOAS system at plant sites was discussed to study the aerosol extinction profile variation for a better estimation. Thereby these systems need to fulfill certain criteria: as LIDAR systems have an overlap problem with the nearest meters to the instrument, a scanning device would be necessary. The use of several wavelengths would increase the information content while it would also enhance the costs and complicate the operability. On the other hand the passive MAX DOAS system could derive profile information by using several mirrors (so called retros) at the plant tower. A field campaign to study the advantages of active profile measurements over the assumption of a well-mixed boundary layer would be advisable for future research.

Parameterizations to derive the horizontal transmittance at ground level using the available data sets have to be developed or enhanced and can be validated with the now existing measurement systems of [1] or [2]. To identify global atmospheric extinction data sets will reduce the CSP plant simulation uncertainty and hence also the costs of the tower plant project as risk margins of banks and engineering, procurement and construction contractors will be lowered [40].

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