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Evaluating solar radiation attenuation models to assess the effects of climate and geographical location on the heliostat field efficiency in Brazil

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Abstract

Most of the solar power plants using a central receiver which are currently in operation are installed in the Sun Belt region, specifically above the Tropic of Cancer. These plants are located in regions characterized by a dry summers and a yearly sum of Direct Normal Irradiation (DNI) of over 2300 kWh/m². These regions include the Mojave Desert (semi-arid climate) and Andalucía in southern Spain (Mediterranean and semi-arid climate). Potential locations for installing such plants in Brazil, identified in previous studies, are the São Francisco river basin and the Sobradinho area in the Northeast Region of the country. These locations are characterized by high humidity levels and yearly DNI values ranging from 1800 to 2300 kWh/m², which is in clear contrast with the dry and desert climates where the solar tower projects currently in operation are located. Besides the combined effects of climate and the inter-tropicalization of the site, based on the solar angles and atmospheric attenuation, the potential locations in Brazil provide a small variation between the monthly averages DNI values. In this paper, the effects of these particularities on the performance of a heliostat field are assessed. For instance, the effects of the atmospheric water vapor and aerosol concentration on the optical performance of the heliostat field are analyzed. The results suggest that, for the same DNI level, the heliostat field in Brazil should be 4% larger due to the effect of the water vapor concentration in the atmosphere. This is an important finding, which shows that the current models for calculating the attenuation between the heliostat and the receiver need to be reviewed and compared with experimental observations and validated for the conditions prevailing at potential locations in Brazil.

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1. Introduction

Concentrated solar power (CSP) technologies have gained increasing attention in recent years, since they present several advantages allowing their combination with thermal energy storage, enabling to shift solar radiation according to the energy demand and increasing the energy dispatchability. To date, the global stock of CSP plants represents 1700 MW of installed capacity. Projects now under construction account for a further 2100 MW, and plans are underway for an additional 14200 MW worldwide [1, 2]. Of the CSP technologies currently available, the parabolic trough is the most mature, accounting for around 90% of the aforementioned projects. However, in recent years, the central tower power system (also known as the solar tower) has gained increasing attention due to the possibility of achieving higher temperatures and therefore better efficiencies [2, 3]. In addition, central tower power systems have some advantages when compared to parabolic trough systems, such as lower thermal losses, since the working fluid travels shorter distances through the receiver system, decreasing the thermal energy losses. However, central tower systems use hundreds or thousands of heliostat mirrors in order to concentrate the solar radiation and this radiation must travel through the solar field in order to reach the receiver. In this context, one major limitation regarding the size of the solar field is the distance that a heliostat can be placed from the tower, because the beam radiation is attenuated as it travels from the heliostat to the receiver. Hence, not all of the solar radiation that leaves the heliostats reaches the vicinity of the receiver, some of this energy being scattered and absorbed by the atmosphere. These attenuation losses represent a small portion on a clear day; however, they increase in the presence of high aerosol or water vapor content, and can reach over 20% of the incident radiation on the heliostat. Since the attenuation loss has been recognized as a significant source of loss in solar tower power plants, it is necessary to perform a detailed assessment of the influence of these variables on the attenuation losses, in order to evaluate the feasibility of large solar tower plants.

The potential locations for installing such plants in Brazil, identified in previous studies, are the São Francisco river basin and the Sobradinho area, in the Northeast Region of the country [4]. These locations are characterized by high humidity rates and a yearly Direct Normal Irradiation (DNI) value ranging from 1800 to 2300 kWh/m², which is in clear contrast with the dry and desert climates where the solar tower projects currently in operation are located. This contrast is observed in Fig. 1, where mean values for the daily DNI and water vapor concentration in the atmosphere are plotted for three different cities: Bom Jesus da Lapa (BJdL), Bahia State, Brazil, near the São Francisco river basin; Daggett, California State, United States, home of the Solar Two project; and Seville, Andalucía, Spain, at the proximity of Planta Solar 20 (PS20) solar power plant. As shown in Fig. 1a, although Bom Jesus da Lapa has lower rates of DNI compared to Daggett, its rates are similar to those of Seville. Also, this Brazilian city has a lower seasonal variability in relation to the DNI, which could allow constant operation of the plant throughout the year. However, as seen in Fig. 1b, the water vapor concentration of atmospheric air at Bom Jesus da Lapa is significantly higher than those reported for Daggett and Seville. This paper presents a comparison of the available atmospheric attenuation models, in order to assess their applicability to inter-tropical regions and selecting the appropriate model to analyze the effects of the particular characteristics of the Northeast Region of Brazil on the heliostat field.

2. Methodology

In order to assess the atmospheric attenuation of the reflected solar irradiance in Bom Jesus da Lapa, three different models [5, 6, 7] were applied. The results of these models were then compared and a seasonality analysis was performed in order to evaluate the effect of high humidity rates on the attenuation losses, disaggregated by season. In addition, each model was used to determine the optical performance and the optimal field layout. This allowed assessing the impact of the use of such models in inter tropical regions. The plant sizing and optimization were carried out using the program Power Tower Generator (PTGen) [8], which consists of a Fortran code and a graphic user interface. PTGen uses the DELSOL3 code [9] alongside other Fortran programs. DELSOL3 is applied in three steps. First the solar power plant is iteratively optimized based on the set-points for the user inputs [8]. This plant sizing information is then used to perform the performance calculations, which involve two steps: calculating the heliostat field efficiency and calculating the radiation flux distribution incident on the tower receiver surface.
The outputs of the PTGen can be classified into three categories: plant summary, heliostat field/heliostat parameters and heliostat field net efficiency. The first category includes information on the receiver geometry, while the second includes information on the distribution of the heliostats along the heliostat field. Finally, the heliostat field net efficiency presents the estimated efficiency by the model and the distribution of the flux at the receiver, as a function of the solar position (azimuth and zenith angles).

Fig. 1. Monthly data for different cities. (a) Mean daily DNI, (b) Mean water vapor concentration of atmospheric air.

2.1. DELSOL

To estimate the atmospheric attenuation, which occurs between the heliostat and the receiver, the DELSOL code [9] uses the model developed by Vittitoe and Biggs [5]. These authors applied the LOWTRAN [10] code to model the solar beam propagation between a heliostat and receiver, generating tabulated numerical results. They then presented a polynomial approximation of their results. This model calculates the losses by means of a parametric equation, which is a function of the slant range between the heliostat and the receiver. In order to account for different levels of aerosol content, two equations are employed: one for a clear day (visibility 23 km) and another for a hazy day (visibility 5 km). In this context, the attenuation loss for a clear day is estimated by the following equation

\[
\text{Att} = 100 \cdot (1 - \tau) = 0.6739 + 10.46 R - 1.70 R^2 + 0.2845 R^3
\]  

(1)

whereas the attenuation loss for a hazy day is expressed by,

\[
\text{Att} = 100 \cdot (1 - \tau) = 1.293 + 27.48 R - 3.394 R^2
\]  

(2)

where \(\tau\) is the transmittance in the path between the heliostat and receiver and \(R\) is the slant range. However, the Vittitoe and Biggs model [5] was derived from observations taken at a specified site (Barstow, California, US, at 650 m of elevation) and does not account for the seasonal variation in the atmospheric attenuation and the effects of the site elevation.

2.2. Pitman & Vant-Hull

The model developed by Pitman and Vant-Hull [6] is also based on the tabulated numerical results of Vittitoe and Biggs. However, the Pitman and Vant-Hull model calculates the transmittance in terms of five explicit variables and ten constants obtained from the fitting of these tabulated data. The explicit variables are: site elevation above sea level \(H_s\), the water vapor concentration of the atmospheric air \(\rho_w\), the scattering coefficient \(\beta\) (at wavelength band
around 0.55 μm), the tower focal height \( H_T \), and the slant range \( R \). Also, the model contains three implicit variables: the season of the year, the climatic region and the site elevation \( H_s \). These implicit variables accounts for the seasonal variation of the water vapor density and the scattering coefficient are dependent on the climate and elevation of the site. Concerning the aforementioned considerations, the attenuation loss of the Pitman and Van-Hull model is calculated by using the following equations,

\[
\text{Att}(\%) = 100 \cdot (1 - \tau) = 100 \cdot (1 - \exp(-\xi R^2)) 
\]

(3)

\[
\xi = C \exp(-AH_T) 
\]

(4)

\[
1 - S = S_0 (\beta + 0.0091)^{-1/2} 
\]

(5)

\[
\beta = 3.912/V_R 
\]

(6)

\[
C = C_0 (\beta - 0.0037)^S 
\]

(7)

\[
A = A_0 \ln((\beta + 0.0003\rho_w)/0.00455) 
\]

(8)

\[
C_0 = 0.0105\rho_w + 0.724 
\]

(9)

\[
S_0 = 0.00101\rho_w + 0.0507 
\]

(10)

\[
A_0 = 0.0112 H_s + 0.0822 
\]

(11)

where \( \xi \) is the broadband extinction coefficient averaged over all wavelengths of the solar spectrum, \( R \) is the slant range and \( V_R \) is the visibility. The parameter \( A \) represents the rate at which \( \xi \) decreases in vertical length, \( C \) is the average extinction coefficient for zero tower height, \( S \) is the exponent in the transmission model and \( A_0, C_0 \) and \( S_0 \) are the altitude and water vapor-dependent proportionality constants, respectively. Pitman and Vant-Hull developed this model because the technique used for interpolating and extrapolating the results of Vittioe and Biggs is not clear, and the polynomial approximation cannot safely be extrapolated much beyond the two kilometer range of their tabulated results [6].

2.3. Sengupta & Wagner

Sengupta and Wagner developed an alternative methodology for calculating atmospheric attenuation losses occurring between the heliostat field and receiver from DNI measurements. Under clear sky conditions, extinction of the DNI through either absorption or scattering is primarily due to the aerosol content of the atmosphere [7]. The key factor in this methodology is to determine the relationship between the extinction optical depth for a thick near-surface layer (\( \tau_{\Delta z} \)) and the difference in the extinction optical depths for an atmosphere containing aerosols and a theoretical baseline aerosol-free atmosphere (\( \tau_a - \tau_b \)). In order to determine this relationship, several simulations of the atmosphere were carried out on July 21 in Golden, Colorado, US, varying the levels of aerosol optical depth and solar zenith angle using a numeric algorithm. The outputs of these simulations are the DNI for the clean atmosphere (DNIb) as a function of solar zenith, and the relationship between the difference in the extinction optical depths (\( \tau_a - \tau_b \)) and the optical depth of the near-surface layer (\( \tau_{\Delta z} \)). The relationship found is linear and almost independent of solar zenith angle, but it is expected to depend on altitude and atmospheric constituent concentration profiles. The DNI levels for the clean case should also be dependent on these variables. Considering both this information and the measured DNI data (DNIa), the attenuation between the heliostat and the receiver can easily be calculated as a function of the slant range. Hence, the attenuation between the heliostat field and the receiver is calculated from
hourly irradiation data for a specific location. In this context, the forcing function for the interpolations is defined as the ratio between the DNI at the specified time and the DNI for an ideal condition of no aerosol content, as follows.

\[ F = \frac{DNI_a}{DNI_b} \]  

(12)

According to Sengupta and Wagner [7], the difference between the extinction optical depths is calculated as:

\[ \Delta \tau = \tau_a - \tau_b = -\ln(F) \cos(\theta_z) \]  

(13)

where, \( \theta_z \) is the solar zenith angle, \( \tau_a \) is the extinction optical depth and \( \tau_b \) is the extinction optical depth for the base case with no aerosol. As shown in [7], \( \tau_{\Delta z} \) has a linear relationship with \( X \) and a weak dependence on solar zenith angle. A linear regression of the data gives the following relationship:

\[ \tau_{\Delta z} = 0.2299 X + 0.002674 \]  

(14)

Finally, attenuation between the heliostat and the receiver is calculated by:

\[ \text{Att}(\%) = 100 \cdot \left( 1 - \exp \left( -\frac{\tau_{\Delta z} \cdot R}{0.250} \right) \right) \]  

(15)

where \( \tau_{\Delta z} \) is the extinction optical depth of the 0.250 km thick atmospheric layer near the surface.

The coefficients from equation (14) should vary from place to place since they vary with altitude and the atmospheric constituent profiles. The DNI for an atmosphere with no aerosols as a function of the solar zenith should also vary. However, these relationships have not been determined yet for the specific location considered in this study. Instead, the relationships presented in [7] (eq. (14)) for Golden, Colorado, US were considered, therefore the attenuation losses for Bom Jesus da Lapa calculated with the Sengupta & Wagner model were determined by direct extrapolation. This approximation follows the approach used in performance simulating programs, such as System Advisor Model [11], where the correlations for the atmospheric attenuation between the heliostats and the receiver for specific places [9] are extrapolated.

In order to compare the results obtained from this methodology with other standard methodologies it is necessary to estimate an equivalent visibility (\( V_R \)). This can be carried out using the following expression [6]:

\[ \text{Att}(\%) = 100 \cdot \left( 1 - \exp \left( -\frac{3 \cdot R}{V_R} \right) \right) \]  

(16)

On combining equations 15 and 16 the visibility is expressed by:

\[ V_R = \frac{0.750}{\tau_{\Delta z}} \]  

(17)

where \( V_R \) is the visibility in km and \( \tau_{\Delta z} \) is the extinction optical depth.

3. Results

The three methodologies for estimating the atmospheric attenuation were applied to design a heliostat field of a 50 MW solar tower power plant located in Bom Jesus da Lapa at 440 m above sea level. The radiation data available consist of a TMY developed by the SWERA project [12]. In this regard, the results of the simulations are presented in terms of the atmospheric attenuation, seasonal variations and heliostat field efficiency.

3.1. Attenuation

The DELSOL model contains specific equations for different levels of aerosol, one for clear days (23 km of visibility) and another for hazy days (5 km of visibility), thus no additional information is needed. On the other hand, for the Pitman and Vant-Hull model it is necessary to specify the tower height, the water vapor concentration
and the visibility. In the case of the Sengupta and Wagner model, the DNI level and the solar position (i.e. a time of the day and a day of the year) need to be specified. Under these conditions, a solar tower with a height of 100 m was considered along with the values for the days October 29 and December 17 and the time period between 12:00h and 13:00h (standard time). The DNI level and water vapor concentration at Bom Jesus da Lapa during these periods are 990 Wh/m^2 and 11.2 g/m^3 for October 29 and 688 Wh/m^2 and 19.9 g/m^3 for December 17. The equivalent visibility of these two days, calculated using equation (17) for the Sengupta and Wagner model are 15 km and 5 km, which are values representative of a clear day and a hazy day, respectively. The atmospheric attenuation loss between the heliostat field and receiver over slant range distances for the three models are presented in Fig. 2.

![Fig. 2. Atmospheric attenuation from the heliostat to the receiver over the slant range distance for the three models. (a) clear day, (b) hazy day.](image)

As shown in Fig. 2, there is no agreement between the DELSOL and the other models. This result is consistent with those presented by Ballestrín and Marzo [13]. On the other hand, the Sengupta and Wagner model shows a better agreement with the Pitman and Vant-Hull model. For the clear day, the Sengupta and Wagner model estimates higher attenuation losses for slant range distances greater than 0.6 kilometers. This difference could arise from the fact that the visibility value used in the Pitman and Vant-Hull model is different from that estimated by the Sengupta and Wagner model. Conversely, for a hazy day the Sengupta and Wagner model estimates lower attenuation losses than the Pitman and Vant-Hull model for all slant range distances. These differences probably occur because of the extrapolations used in both models.

Ballestrín and Marzo [13] compared the results obtained applying the DELSOL code, the MIRVAL code [14], the Pitman and Vant-Hull model and the MODTRAN [15] code. This code is, a computer program designed to assess the atmospheric propagation of electromagnetic radiation for the 200-100,000 nm spectral range. The results showed a good agreement between the MODTRAN model and the Pitman and Vant-Hull model, indicating that the latter is more accurate and more versatile than the DELSOL. Therefore, based on this finding, the Pitman and Vant-Hull model was henceforth considered as the reference model.

Recently, Sengupta and Wagner [7] analyzed the differences between the MODTRAN and DELSOL results presented by [13]. They found that the disagreement could be explained by the differences in elevations of the sites simulated in MODTRAN by [13] and Barstow, California, US. They concluded that the DELSOL model is appropriate for that particular elevation (0.7 km), but is not applicable to other elevations without carrying out the necessary corrections. However, the lack of consistency of the DELSOL model is not a problem in itself. The problem consists of using this model in the optimization of the heliostat field design for plants located in locations with significantly different climatological variables without applying the appropriate corrections. Nevertheless, the
approach used consisted of taking a polynomial approximation of the data specific for Barstow inputting it into a computer model and then using it, without modification, for all sites and conditions.

3.2. Seasonality analysis

The Pitman and Vant-Hull model was used to calculate the attenuation losses for Seville, Daggett and Bom Jesus da Lapa. Figure 3 shows the attenuation losses in a one-year period, calculated for a tower with a height of 100 m, 23 km visibility, 1 km slant range, the site elevation of each location and the water vapor concentration in atmospheric air, calculated from TMY data for the three different cities. In this analysis the water vapor concentration is the only time-dependent parameter, therefore the Figure 3 shows the effects of the water vapor’s seasonal variability in the atmospheric attenuation.

It is possible to observe that the attenuation losses and the seasonal fluctuation of those values at the latter location are always higher than the corresponding values for Seville and Daggett. The higher levels of water vapor concentration at Bom Jesus da Lapa increases in 3% the attenuation losses, compared with the attenuation at Daggett. Besides of that, the seasonal fluctuation of the attenuation at Bom Jesus da Lapa (2%) is twice the value at Daggett (1%). Although these values are small, it is crucial to assess the effects of these variables during the design process of the heliostat field and the impacts of neglecting them in long-term performance evaluations.

3.3. Field efficiency

Based on the results shown in Fig. 2a, a polynomial approximation was generated for the Pitman and Vant-Hull and the Sengupta and Wagner models. These polynomials were inputted into the PTGen/DELSOL3 software in order to determine the optical performance and the optimal field layout for each model. The main parameters set in the PTGen were: 50 MW of desired electric power output; 1.3 of solar multiple; 6 m of total heliostat height; 6.6 m of total heliostat width; an external receiver; 100 m of tower height and the coordinates (elevation, latitude and longitude) for Bom Jesus da Lapa. For all the remaining parameters the default values of PTGen were considered. Table 1 shows a summary of the main outputs for the plant sizing and the optimization for each attenuation model assumed. It can be observed that, with the DELSOL attenuation model, the heliostat field is 4% smaller than the field generated with the Pitman and Vant-Hull model. It is clear that the overall efficiency of the DELSOL field will be greater than the overall efficiency of the other two fields. This is borne out of the fact that the attenuation calculated by the DELSOL model is lower than that calculated by the other models. On the other hand, the heliostat fields estimated using the Sengupta and Wagner model and the Pitman and Vant-Hull model are practically equivalent, as expected, since the attenuations calculated with these models are similar (Fig. 2a).
Fig. 3. Seasonal effect of the water vapor density on the atmospheric attenuation, calculated with the Pitman and Vant-Hull model for Bom Jesus da Lapa, Seville and Daggett

Table 1. Plant sizing and optimization for the different attenuation models

<table>
<thead>
<tr>
<th>Results</th>
<th>DELSOL</th>
<th>Pitman &amp; Vant-Hull</th>
<th>Sengupta &amp; Wagner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of heliostats</td>
<td>7900</td>
<td>8241</td>
<td>8251</td>
</tr>
<tr>
<td>Overall Efficiency [%]</td>
<td>21.0</td>
<td>20.2</td>
<td>20.2</td>
</tr>
</tbody>
</table>

The optimized heliostat field layouts calculated with the DELSOL attenuation model and with the Pitman and Vant-Hull model are presented in Fig. 4. The optimized heliostat field layout for the Segupta and Wagner model is not presented since the results were identical to those obtained with the Pitman and Vant-Hull model. These diagrams show that the heliostat field is evenly distributed among 12 azimuthal zones and 12 radial zones, with the color corresponding to the number of heliostats per zone, as indicated on the side bar of each graph. As mentioned above, the heliostat field estimated through the DELSOL model is smaller than that estimated using the Pitman and Vant-Hull model, as can be evidenced in Fig. 4. Both fields are slightly larger at the southern area of the field, which is expected considering the latitude of Bom Jesus da Lapa, 13.3°S. Nonetheless, the heliostats fields estimated using the Pitman and Vant-Hull models are more evenly distributed along the azimuthal zones than the field calculated using the DELSOL program. The first field has only one empty zone at the northern outer ring, while the DELSOL field presents five empty zones in this region. Although this difference is clearly observed in the Figures 4a and 4b, 52.7% of the heliostats of the Pitman and Vant-Hull model are located in the southern region, while in the case of the DELSOL field 53.6% of the heliostats are in this area.
In order to assess the effect of using the different attenuation models on the performance of the central tower system, the differences between the heliostat field net efficiencies of the DELSOL model and the Pitman and Vant-Hull model were calculated. The relative error between the net field efficiency as a function of the solar position is shown in Fig. 5. The mean relative error between the net field efficiencies was 4%. This result, combined with those presented by [13], suggests that using the DELSOL model to design a heliostat field for locations with significantly different climatological variables, without applying the appropriate corrections, can result in under sizing the heliostat field by a factor of around 4%. This also indicates a lower radiation flux at the receiver and a consequently lower energy production. Nevertheless, DELSOL is still used as a tool in transient performance evaluation programs [11]. Since the long-term performance of solar tower power plants needs to be evaluated for economic feasibility studies, a 4% difference in the heliostat field size could be very significant in long-term systems analysis, and thus an appropriate methodology that accounts for different levels of aerosol content and/or water vapor density needs to be developed.
4. Conclusions and further studies

An analysis of three different models available for calculating attenuation losses between the heliostat and the receiver was performed. The results obtained by applying three models did not present good agreement. This finding was expected considering the extrapolations carried out by the DELSOL and the Sengupta and Wagner models. The results showed that DELSOL undersizes the heliostat field by around 4% when compared to the Pitman and Vant-Hull model. This could mean a significant source of errors in long-term performance evaluations; therefore a major study on the accuracy of these models should be performed.

The results suggest that the methodology developed by Sengupta and Wagner is a feasible alternative for atmospheric attenuation calculations. In order to evaluate these effects, a more detailed analysis needs to be carried out, without considering the extrapolations either for the coefficients or for the DNI baseline case, which considers an atmosphere with no aerosols. In future studies these variables will be calculated for the specific case under study using atmospheric transmittance simulating programs, such as MODTRAN, applying the methodology described in [7] and measured atmospheric content profiles as inputs. Attenuation estimates will also be updated using the Pitman and Vant-Hull model and measured visibility data. Moreover, the MODTRAN will be used to model the solar beam propagation between a heliostat and receiver, like described in [13], to generate tabulated numerical results, and develop a new model for Brazilian locations. This analysis will give a complete framework for comparing and validating the attenuation losses at inter-tropical locations.

Acknowledgements

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