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Modeling water vapor impacts on the solar irradiance reaching the receiver of a solar tower plant by means of artificial neural networks

Gabriel López[a,*], Christian A. Gueymard[b], Juan Luis Bosch[a], Igor Rapp-Arrarás[c], Joaquín Alonso-Montesinos[d], Inmaculada Pulido-Calvo[c], Jesús Ballestrín[e], Jesús Polo[f], Javier Barbero[d]

[a] Dpto. Ingeniería Eléctrica y Térmica, de Diseño y Proyectos, Universidad de Huelva, Huelva, Spain
[b] Solar Consulting Services, P.O. Box 392, Colebrook, NH 03576, USA
[c] Dpto. Ciencias Agroforestales, Universidad de Huelva, Huelva, Spain
[d] Dpto. Química y Física, University of Almería, Almería, Spain
[e] Concentrating Solar System Unit (Plataforma Solar de Almería, CIEMAT), Almería, Spain
[f] Photovoltaic Solar Energy Unit (Renewable Energy Division, CIEMAT), Madrid, Spain

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ABSTRACT

This work analyses the influence of water vapor on the atmospheric transmission loss of solar radiation between heliostats and the receiver of solar power tower plants. To this purpose, an atmospheric transmission code (MODTRAN) is used to generate values of direct normal irradiance (DNI) reaching the mirror and the receiver under different geometries (including sun position, tower height, and mirror-to-receiver slant range) and atmospheric conditions related to water vapor and aerosols. These variables are then used as inputs to an artificial neural network (ANN), which is trained to calculate the corresponding DNI attenuation. Two different aerosol scenarios are simulated: an ideal aerosol-free atmosphere, and a widely different one corresponding to semi-hazy conditions. The developed ANN model is then able to provide the DNI attenuation over a wide range of the input variables considered here, with root mean square differences of only 0.8%. The transmission loss due to water vapor is found to decrease with sun elevation. This is explained by the saturation effect in the incident irradiance at the mirror. The simplicity and accuracy of the algorithm are its great strengths, allowing its anticipated inclusion into the actual energy simulation codes currently used for solar tower plant design.

1. Introduction

Estimation of direct normal irradiance (DNI) is a research topic of increasing interest in solar energy, particularly for concentrating solar power (CSP) production. Power generation from Solar Power Towers (SPT), for which DNI is a critical input, is experiencing a rapid growth worldwide, linked to a rapid increase in the generated power and quasi-baseload opportunities offered by high-temperature heat storage. It is anticipated that the SPT technology will be one of the main contributors to the future mix of renewable energies. The greater challenges posed by these large solar installations is their complexity and cost. Economies of scale are possible, but require large installations, where the outer heliostats can be a few kilometers away from the receiver. To guarantee a good design and estimate of the electricity production under any circumstances, it is crucial to have an accurate evaluation of the DNI received by the receiver from each heliostat at any instant, since this ultimately affects the operation and revenue, as well as the energy price market.

Under cloudless conditions, aerosols and water vapor have relatively high concentrations near the ground and thus are the main variable atmospheric constituents attenuating the DNI after reflection by heliostats. As a matter of fact, experience has shown that the heliostat-to-tower attenuation can reach substantial levels in cases of high turbidity and/or humidity content near ground level. For instance, Saharan dust outbreaks in southern Spain are not rare, and produce significant attenuation levels. Fig. 1 clearly illustrates the optical effect of such an event, which occurred in February 2016 at the Plataforma Solar de Almería (PSA) research center (Spain). That specific event and ensuing DNI attenuation are further analyzed by Alonso-Montesinos et al. (2017).

The above-mentioned dust outbreaks occur several times a year, affecting the production of all solar tower plants installed in Andalusia,

* Corresponding author.
E-mail address: gabriel.lopez@die.uhu.es (G. López).

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Fig. 1. Low visibility and substantial light scattered by large particles in the atmosphere at PSA on 2016-02-22 at 14:30 local time. Solar radiation reflected by the heliostats is visibly attenuated by scattering.

in particular. Such episodes are even more frequent in northern Africa, the Middle East, or Asia, where a rapid growth in the number of installed SPT plants is expected. Consequently, the specialized computer codes commonly used by engineers for plant sizing or energy simulation of SPT systems should include the effects of these extreme atmospheric conditions, while being also flexible and general in order to be used under a variety of climates, etc. Unfortunately, the models that can estimate such losses were typically developed several decades ago (Vittitoe and Biggs, 1978; Pitman and Vant-Hull, 1982), and are insufficient to meet the increased accuracy demanded by new SPT projects. Ballestrín and Marzo (2012) have compared the atmospheric mirror-to-receiver (MTR) attenuation results from the above-mentioned simple algorithms to detailed simulations obtained with the rigorous MODTRAN atmospheric spectral code (Berk et al., 1989) for a rural-type atmosphere. Although the Pitman and Vant-Hull model showed good results, both for turbid and clean conditions, only two different turbidity conditions were simulated, which is far from representing all possible conditions at any one SPT site.

In perspective, it is important to estimate the direct value of better evaluating atmospheric attenuation losses. The sizing of the heliostats field using different SPT design codes such as DELSOL or MIRVAL can present deviations up to 4% when considering variable conditions of aerosols and water vapor, leading to significant economic repercussions (Cardemil et al., 2014). Polo et al. (2017) have found differences of up to 20% in the energy output production of large SPT plants depending on the time-scale input information (e.g. daily, monthly or yearly values) used to model the atmospheric extinction. These findings support the need of analyzing and modeling the effects of different atmospheric components, such as aerosols or water vapor, on the MTR attenuation at fine temporal resolution. Theoretical simulations conducted by means of spectral radiative codes, such as MODTRAN, show that reductions up to 30% in solar irradiance incident on distant heliostats can occur under moderately turbid conditions (López et al., 2017).

In recent years, methods for the direct or indirect experimental determination of the horizontal extinction coefficient or of the energy attenuation have been proposed. For instance, Sengupta and Wagner (2012) proposed to derive the MTR attenuation from the measurement of DNI with two pyrheliometers, one measuring the incident DNI on the mirror (or heliostat), and the other one measuring the DNI incident on the receiver. The authors noted the great difficulties inherent to this methodology (depending on the reflectance of mirrors, their cleanliness variations in local conditions, etc.), and the crucial importance of measurement errors. Tahboub et al. (2014) used measurements from four pyrheliometers installed on the side of a mountain and staggered at various elevations (from 340 to 1035 m) to study the correlation between the DNI measurements thus obtained at different heights. More generally, a thorough review of experimental methods and atmospheric attenuation models can be found in the recent literature (Hanrieder et al., 2017). Even though the current knowledge points at aerosols as the main source of slant MTR attenuation, there is no exhaustive study analyzing the relative importance of other atmospheric variables, such as water vapor, and their effects on energy losses.

In this work, the radiation losses specifically caused by air molecules and water vapor are analyzed, and a preliminary soft-computing algorithm is proposed to evaluate them with sufficient accuracy. To that end, the spectral propagation of DNI from the top of the atmosphere to the receiver is simulated with MODTRAN for several air masses, also taking the atmospheric composition into account. The dependence of the attenuated DNI on solar zenith angle, amount of water vapor, MTR distance, and others factors, is analyzed toward the development of a general prediction model.

Using conventional methods, the complex non-linear relationships between the various atmospheric or geometric inputs and transmission loss lead to excessive difficulties in finding a suitable mathematical function. An artificial neural network (ANN) is thus rather developed here to obtain transmission loss estimates from the inputs considered. In addition to the multiple applications of ANN methods in pattern recognition and classification, function approximation, prediction, etc., their usage in data analysis is growing fast, offering an effective alternative to more traditional techniques in many scientific fields. Particularly, in the meteorological and solar energy resource fields, ANN-based methods have been successfully developed to evaluate various solar radiation variables, thus improving their accuracy with respect to more conventional statistical approaches (Bosch et al., 2008; Eissa et al., 2013; López and Gueymard, 2007; Srikrishnan et al., 2015). Moreover, ANNs are starting to be used to estimate solar irradiance with a similar degree of accuracy as what can be achieved by the more conventional methods based on broadband or spectral radiative models (Takenaka and Nakajima, 2011; Taylor et al., 2015). Thus, this emerging application of ANN allows efficient (fast and accurate) calculations of the otherwise computationally expensive and complex mathematical formulations involved when using conventional spectral radiative transfer models.

2. Methodology

2.1. Generation of synthetic data

The MODTRAN model is used here to obtain hundreds of initial predictions of the incident DNI, both at the mirror M (E_M) and at the receiver on the tower T (E_T), after E_M is reflected by M (Fig. 2). These simulations pertain to a large range of solar zenith angles (Θ_z), mirror-to-receiver slant ranges (S), tower heights (H), precipitable water (w), and two widely different turbidity conditions. These initial, spectrally-based predictions are used as the foundation of the proposed ANN model.

As modeled in MODTRAN, the spectral transmittance between M

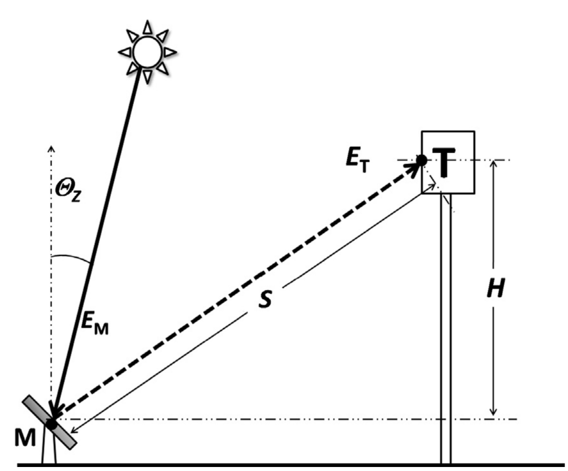

Fig. 2. Schematic description of the tower power plant and nomenclature.