Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 117 (2015) 125–138

SOLAR ENERGY

www.elsevier.com/locate/solener

Impact of local broadband turbidity estimation on forecasting of clear sky direct normal irradiance

Rich H. Inman, James G. Edson, Carlos F.M. Coimbra *

Department of Mechanical and Aerospace Engineering, Jacobs School of Engineering, Center for Renewable Resource Integration and Center for Energy Research, University of California, San Diego, La Jolla, CA 93093, USA

Received 25 March 2014; received in revised form 13 April 2015; accepted 26 April 2015
Available online 16 May 2015

Communicated by: Associate Editor Christian A. Gueymard

Abstract

Clear-sky modeling is of critical importance for the accurate determination of Direct Normal Irradiance (DNI), which is the relevant component of the solar irradiance for concentrated solar energy applications. Accurate clear-sky modeling of DNI is typically best achieved through the separate consideration of water vapor and aerosol concentrations in the atmosphere. Highly resolved temporal measurements of such quantities is typically not available unless a meteorological station is located in close proximity. When this type of data is not available, attenuating effects on the direct beam are modeled by Linke turbidity-equivalent factors, which can be obtained from broadband observations of DNI under cloudless skies. We present a novel algorithm that allows for a time-resolved estimation of the average daily Linke turbidity factor from ground-based DNI observations under cloudless skies. This requires a method of identifying clear-sky periods in the observational time series (in order to avoid cloud contamination) as well as a broadband turbidity-based clear-sky model for implicit turbidity calculations. While the method can be applied to the correction of historical clear-sky models for a given site, the true value lies in the forecasting of DNI under cloudless skies through the assumption of a persistence of average daily turbidity. This technique is applied at seven stations spread across the states of California, Washington, and Hawaii while using several years of data from 2010 to 2014. Performance of the forecast is evaluated by way of the relative Root Mean Square Error (rRMSE) and relative Mean Bias Error (rMBE), both as a function of solar zenith angle, and benchmarked against monthly climatologies of turbidity information. Results suggest that rRMSE and rMBE of the method are typically smaller than 5% for both historical and forecasted CSMs, which compare favorably against the 10–20% range that is typical for monthly climatologies.

Keywords: Direct normal irradiance; Linke turbidity; Solar forecasting; Aerosols

---

1. Introduction

Knowledge of clear-sky irradiance plays a critical role in several solar engineering applications including the definition of clear-sky indices, the development of smart persistence forecasts, the normalization of information retrieved from satellite data, and the calculation of forecasting skill metrics (Inman et al., 2013). In particular, clear-sky modeling is essential for the accurate determination of Direct Normal Irradiance (DNI) under cloudless skies. DNI is the critical component of the solar irradiance for Concentrated Solar Power (CSP) applications such as the recently completed Ivanpah Solar Electric Generating System located in the Mojave Desert of California, which at the time of writing is the largest solar thermal project in the world (392 MW). Although CSP technologies currently represent only a small fraction of renewable energy

---

* Corresponding author.
E-mail address: ccoimbra@ucsd.edu (C.F.M. Coimbra).

http://dx.doi.org/10.1016/j.solener.2015.04.032
0038-092X/

portfolios on a global scale, annual energy generated from such technologies are expected to exceed 30 TW h by 2017 (IEA, 2013).

Increased CSP market share will require further policy action to tackle technical and financing challenges that currently hinder deployment (IEA, 2014). One approach to lower the cost of grid integration is the application of DNI/CSP forecasting, which makes CSP plants more financially attractive to deploy. These forecasts are used to determine optimal operational strategies that maximize profit by minimizing penalty charges resulting from differences between plant output and forecasted output. As a result of CSP plants being driven by DNI, the determination of such optimal operational strategies for CSP plants depends strongly on the accuracy of DNI forecasting. In general, forecast uncertainties are driven by variability in cloud cover. However, it is well known that under cloudless skies the presence of aerosol particles and water vapor become the most important factors influencing the intensity of ground level DNI (Gueymard, 2012a; Eltbaakh et al., 2012).

The term *aerosol* is used to describe either liquid or solid particles that are suspended in the atmosphere with sizes ranging from 1 to 10^5 nm in radius (Wen, 1996). Aerosols in the atmosphere may be either natural or anthropogenic in origin and include particles such as fine soil, pollen, and microorganisms lifted by the wind; sea salts escaping from breaking waves; smoke and soot emitted from fires; ash and dust erupting from volcanoes; sulfates created by the burning of coal and oil; and black carbon released during the incomplete combustion of heavy petroleum products. The net effect of aerosols on local microclimates depend on three primary mechanisms: direct radiative forcing as a result of scattering and absorption of visible and infrared radiation in the atmospheric boundary layer, indirect radiative forcing associated with changes in the microphysical and optical properties of cloud fields, and local heating in the cloud formation layer due to highly absorbent aerosols such as black carbon (Stefan et al., 2006). Although it is clear that DNI attenuation under cloudless skies is driven by aerosol variability, the magnitude of these influences is poorly constrained as a result of the highly spatial–temporal variability of aerosol particles in the atmosphere as well as the fragmentary knowledge of the processes which control the physical, chemical, and optical properties of aerosol distributions (Morcrette et al., 2003; Kaskaoutis and Kambezidis, 2008; Chin et al., 2002).

Several methods for the quantification of atmospheric aerosol loading are available in the literature including both ground-based and remote sensing techniques (see Section 2). While current satellites provide daily multi-wavelength AOD data for nearly any location on the planet, their quality is questionable at times as a result of missing pixels in AOD retrievals and cloud contamination. Ground-based pyrheliometers, on the other hand, are typically located at CSP sites and offer a highly resolved temporal signal of DNI, which under cloudless skies is related to atmospheric aerosol loading. Therefore, highly temporally resolved ground-based observations of DNI under clear skies allow for a robust sampling of local turbidity, specifically at locations of interest to CSP plant operators.

Several authors have examined the derivation of atmospheric aerosol loading from broadband irradiance measurements. More specifically, Louche et al. (1987) assigned a fixed value to the Ångström exponent α (see Section 2) and calculated the Ångström turbidity coefficient β from DNI observations over Ajaccio (France). Gueymard and Vignola (1998) developed a semi-empirical model that demonstrated the utility of the diffuse component of broadband irradiance for estimating atmospheric turbidity. Cañada et al. (1993) also assigned a fixed value to α in order to estimate β in Valencia (Spain) and compared the results with those from Ajaccia, Avignon, and Dhahran. Ineichen (2008) presented a conversion function between T_{LI}, the atmospheric water vapor and urban aerosol content that also accounts for the altitude of the application site.

More recently, Polo et al. (2009) proposed a method to estimate daily Linke turbidity factor by using global irradiance measurements at solar noon. Gueymard (2013) provided an efficient method to derive Aerosol Optical Depth (AOD) information from broadband DNI measurements and addressed several critical issues including: instrument error, impact of model performance, propagation of errors due to incorrect precipitable water, elimination of cloudy conditions, and evaluation of α. Gueymard (2014) also evaluated the impact of on-site atmospheric water vapor estimation methods on the accuracy of local solar irradiance predictions. Bilbao et al. (2014), proposed a method for deriving Ångström's turbidity coefficient and the AOD at 550 nm from broadband DNI observations over Castilla y León (Spain), from July 2010 to December 2012.

In addition to the implicit calculation of aerosol loading from irradiance observations, detailed algorithms exist in the literature that produce aerosol forecasts for aerosol fields using remote sensing techniques and transport models, see for example Masmoudi et al. (2003). However, this contribution demonstrates the utility of ground-based estimations of average daily turbidity for the day-ahead forecasting of broadband clear-sky DNI at a specific site. Because of CSP's dependance on broadband DNI, this irradiance component tends to be measured on site resulting in readily available broadband turbidity information at such locations. An endogenous clear-sky detection algorithm for DNI is developed, which is based on the work of Reno et al. (2012), and applied to nearly ten site-years of data from seven stations spread across the states of California, Washington, and Hawaii (see Fig. 3). These data represent a number of widely varying microclimates which are used to speak to the robustness of the algorithm. Observations of clear-sky DNI are subsequently used to calculate the daily average air mass independent Linke