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A new approach to the real-time assessment and intraday forecasting of clear-sky direct normal irradiance

Rémi Chauvin[a], Julien Nou[a], Julien Eynard[a,b], Stéphane Thil[a,b], Stéphane Grieu[a,b,*]

[a] PROMES-CNRS (UPR 8521), Rambla de la thermodynamique, Tecnosud, 66100 Perpignan, France
[b] Université de Perpignan Via Domitia, 52 Avenue Paul Alduy, 66860 Perpignan, France

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ABSTRACT

Clear-sky Direct Normal Irradiance (DNI) is the solar power received at ground level per unit of area, at a specific location, under cloud-free conditions. Regarding Concentrating Solar Power (CSP) technologies, such conditions mean that there is no cloud between the Sun and the observer, i.e. the solar field. Since clear sky defines the nominal operating conditions of CSP plants, real-time estimates and forecasts of clear-sky DNI are key information for power plant operators tasked with the management of those plants. So, the present paper focuses first on a new algorithm for the real-time detection of clear-sky situations from DNI measurements. This algorithm makes use of the last-known clear-sky situation and requires the maximum speed at which the atmosphere becomes opaque to be evaluated. The paper also focuses on an efficient approach to the real-time assessment of clear-sky DNI. This approach combines the model developed by Ineichen and Perez with a persistence of atmospheric turbidity, taking advantage of the fact that changes in this quantity are relatively small throughout the day in comparison to changes in DNI, even when the sky is free of clouds. Performance is evaluated via a comparative study, in which empirical models are included, using one-minute data from two sites (Golden, USA, and Perpignan, France). MAE and RMSE are lower than 10 W m^{-2} and 21 W m^{-2}, respectively. The same approach is capable of providing accurate intraday forecasts of clear-sky DNI. It has proven to be the best compromise between accuracy and complexity (reference is a persistence of DNI) among the considered approaches, including neuro-fuzzy approaches. For a forecast horizon of 5 h,MAE $\simeq$ 30 W m^{-2} and RMSE $\simeq$ 37 W m^{-2}.

1. Introduction

In CSP plants, production is directly impacted by both the availability and variability of the solar resource and, more specifically, by direct normal irradiance (DNI). The strict definition of DNI, which is the direct irradiance received on a plane normal to the Sun, refers to photons that did not interact with the atmosphere on their way to the observer, i.e. the solar field (Blanc et al., 2014). DNI (noted I) can be split into two terms, i.e. clear-sky DNI (I_{cs}) and the clear-sky index (k_c) (1):

$$I = I_{cs} \cdot k_c \quad (1)$$

I_{cs}, on which the present paper focuses, is the solar power received at ground level per unit of area, at a specific location, under cloud-free conditions. Clear-sky situations are situations in which there are no clouds between the Sun and the solar field, although there may be clouds in the rest of the sky dome, inasmuch as DNI is not affected by diffuse radiation (Larrañeta et al., 2017). Since clear sky defines the nominal operating conditions of the plants (it is directly related to the upper limit of the available solar energy), this is key information for power plant operators. k_c is derived from the attenuation of DNI caused by sun-blocking clouds. It spans from 0, when the path to the observer is obstructed by a thick cloud, to 1, when there is no cloud between the Sun and the observer. Under clear-sky conditions, (1) becomes (2):

$$I = I_{cs} = I_0 \cdot \exp(-m \cdot \tau_{cs}) \quad (2)$$

where I_0 is the extraterrestrial solar irradiance, m is the relative optical air mass and τ_{cs} is the total optical thickness of a cloudless atmosphere.

τ_{cs} is a key parameter in accurately assessing the state of the atmosphere and, as a consequence, the amount of solar energy reaching the ground (Davies and McKay, 1982; Gueymard, 2008; Gueymard and Myers, 2008). Usually, DNI is measured on site using a pyrheliometer or a Rotating Shadowband Irradiometer (RSI). So, power plant operators are notified of the amount of irradiance received by the solar field in real time. However, they don't know if the current situation is clear sky or not. As a consequence, two main objectives are to detect (in real time) clear-sky situations and, in case the current situation is not clear sky, to estimate clear-sky DNI. So, the present paper focuses on

* Corresponding author at: PROMES-CNRS (UPR 8521), Rambla de la thermodynamique, Tecnosud, 66100 Perpignan, France.
E-mail address: stephane.grieu@promes.cnrs.fr (S. Grieu).

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developing both a real-time detection algorithm for clear-sky situations and an efficient approach for clear-sky DNI assessment. Finally, one can try to forecast (over the next hours) clear-sky DNI in order for operators to adapt power plant operation and improve performance in electricity generation. The proposed approach has to be easy to implement and robust to climatic conditions.

The present paper is organized as follows: Section 2 surveys the state of the art of clear-sky DNI models. The main radiative transfer models and empirical models reported in the scientific literature are discussed. Section 3 is first dedicated to the development of a real-time detection algorithm for clear-sky situations, based on DNI measurements. The algorithm makes use of the last-known clear-sky situation and requires the maximum speed at which the atmosphere becomes opaque, hereafter called "maximum opacification speed of the atmosphere", to be evaluated. Regarding the real-time assessment of clear-sky DNI, an approach that combines an empirical model with a persistence of atmospheric turbidity is proposed. It takes advantage of the fact that changes in this quantity are relatively small throughout the day in comparison to changes in DNI, even when the sky is free of clouds. Intraday forecasting clear-sky DNI relies on the same approach. Performance is evaluated via comparative studies in which persistence models as well as artificial-intelligence-based models are included (Section 4). The paper ends with a conclusion and an outlook to future work (Section 5).

2. State of the art of clear-sky DNI models

Regarding clear-sky DNI, models are divided into two categories: empirical models and radiative transfer models (Gueymard, 2012a; Engerer and Mills, 2015; Gueymard and Ruiz-Arias, 2015). Radiative transfer models are derived from the Beer-Lambert law (2), combined with formulations describing, more or less accurately, the interactions between sunlight and atmospheric particles (or aerosols). Indeed, sunlight's transmission through the atmosphere is affected by absorption and scattering of these particles. Both effects produce a selective attenuation of solar radiation. As a consequence, the transmittance of the atmosphere (T) can be formulated as follows (3):

$$T = T_{ra}\cdot T_{O_3}\cdot T_{NO_2}\cdot T_{H_2O}\cdot T_{AOD}\cdot T_g \tag{3}$$

where T_{ra},T_{O_3},T_{NO_2},T_{H_2O},T_{AOD} and T_g are the band transmittances of Rayleigh scattering, uniformly mixed gases absorption, ozone absorption, nitrogen dioxide absorption, water vapor absorption, and aerosol absorption, respectively.

This formulation has been the starting point in the development of clear-sky DNI models based on accurately estimating the state of the atmosphere (Davies and McKay, 1982; Mueller, 2004; Gueymard, 2008). Among the radiative models one can find in the scientific literature, REST2 (Gueymard, 2008) has proven to assess clear-sky DNI with unsurpassed accuracy. Highly complex phenomena that involve interactions between sunlight and atmospheric particles are considered in that model. In addition, REST2 includes two spectral bands with distinct transmission and scattering properties. Clear-sky DNI is estimated using Eq. (2), with T (3) standing in for the term "$\exp(-m\tau_{cs})$". Although radiative transfer models often produce better estimates of clear-sky DNI than empirical models, they need input data that might be not available at any time. Indeed, aerosol optical depth data are required but happen to be difficult to obtain, as well as rarely available (Gueymard, 2012b). Satellite imagery can be used to access the aerosol content in the atmosphere (Schroedter-Homscheidt and Oumbe, 2013; Schepanski et al., 2015). However, temporal and spatial resolutions of satellite images are not enough and REST2 is not suitable for intraday clear-sky DNI forecasting, at a scale of a CSP plant. A localized approach is needed. Radiative transfer models do not cope with real-time applications.

Regarding empirical models, several levels of complexity can be distinguished. Usually, the simplest clear-sky DNI models are based on the solar zenith angle as well as empirical correlations derived from experimental measurements (Paltridge and Proctor, 1976; Meinel and Meinel, 1976; Daneshyar, 1978). Clear-sky DNI can also be computed from an eighth-order polynomial of the cosine of the solar zenith angle (Chu et al., 2013; Quesada-Ruiz et al., 2014). Accuracy of these models is negatively impacted by the lack of information about the state of the atmosphere. In 2015, Gueymard and Ruiz-Arias (2015) highlighted that in arid areas with a high concentration of aerosols, this lack of information can lead to significant errors in clear-sky DNI estimation.

So, several studies have been dedicated to developing more efficient models based on on-site DNI measurements. Note that changes in the transparency of the atmosphere can be grasped through the inversion of (2). Such models, although less accurate than radiative transfer models, are easy to implement and provide estimates with high temporal and spatial resolutions. The first model based on measurements has been developed by Linke (1922). In 1922, he proposed to express the total optical thickness of a cloudless atmosphere (τ_{cs}) as the product of the optical thickness of a water- and aerosol-free atmosphere (i.e. a clean and dry atmosphere) (δ_{cda}) and the Linke turbidity coefficient (T_L), which is defined as the number of clean and dry atmospheres that would be necessary to produce the same attenuation of the extraterrestrial solar irradiance that is produced by the real atmosphere (4):

$$\tau_{cs} = \delta_{cda}\cdot T_L \tag{4}$$

So, clear-sky DNI can be formulated as follows (5), by combining Eqs. (2) and (4):

$$\hat{I}_{cs} = I_0\cdot\exp(-\delta_{cda}\cdot T_L\cdot m) \tag{5}$$

where I_0 is the extraterrestrial solar irradiance (Appendix B) and m is the relative optical air mass (Appendix C).

In 1980, Kasten proposed the following formulation for the optical thickness of a water- and aerosol-free atmosphere (Kasten, 1980), which is known as the "Kasten's pyrheliometric formula" (6):

$$\delta_{cda}^{Kasten} = \frac{1}{9.4 + 0.9\,m} \tag{6}$$

The "Kasten-reviewed Linke turbidity coefficient", noted T_{LK} (7), is then obtained by inverting Eq. (2):

$$T_{LK} = \frac{9.4 + 0.9\,m}{m}\cdot\ln\left(\frac{I_0}{I_{cs}}\right) \tag{7}$$

After new measurement campaigns, many other formulations for the optical thickness of a water- and aerosol-free atmosphere (i.e. a clean and dry atmosphere) (δ_{cda}) have been proposed. All of these formulations are based on a fourth-order polynomial of the relative optical air mass (Louche et al., 1986; Grenier et al., 1994; Kasten, 1996). Among all these works, one can highlight the formulation proposed by Kasten (1996). It is used to estimate solar radiation at ground level from satellite images, in the framework of the new digital European Solar Radiation Atlas (ESRA) (Rigollier et al., 2000) (8):

$$\delta_{cda}^{ESRA} = \frac{1}{a_0 + a_1\cdot m + a_2\cdot m^2 + a_3\cdot m^3 + a_4\cdot m^4} \tag{8}$$

where $a_0 = 6.6296$,$a_1 = 1.7513$,$a_2 = 0.1202$,$a_3 = 0.0065$ and $a_4 = 0.00013$.

This new formulation changes the associated Linke turbidity coefficient. However, for a given measurement, τ_{cs} has to remain unchanged. This constraint, as well as Eq. (4), bind the Kasten-reviewed Linke turbidity coefficient (T_{LK}) to T_{LE} as follows (9):

$$\tau_{cs} = \delta_{cda}^{Kasten}\cdot T_{LK} = \delta_{cda}^{ESRA}\cdot T_{LE} \tag{9}$$

For standardization reasons, the Kasten-reviewed Linke turbidity coefficient has been widely used by the scientific community. In addition, because T_{LK} has a strong dependence on the relative optical air mass (Kasten, 1988; Kasten and Young, 1989; Grenier et al., 1994; Eltbaakh et al., 2012), an air mass equal to 2 (noted AM2) has been considered as standard in almost all studies to date dealing with clear-