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Technical note

Evaluation of decomposition models of various complexity to estimate the direct solar irradiance over Belgium

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ABSTRACT

Solar energy production is directly correlated to the amount of radiation received at a given location. Appropriate information on solar resources is therefore very important for designing and sizing solar energy systems. Concentrated solar power projects and photovoltaic tracking systems rely predominantly on direct normal irradiance (DNI). However, the availability of DNI measurements from surface observation stations has proven to be spatially too sparse to quantify solar resources at most potential sites. Satellite data can be used to calculate estimates of direct solar radiation where ground measurements do not exist. Performance of decomposition models of various complexity have been evaluated against one year of in situ observations recorded on the roof of the radiometric tower of the Royal Meteorological Institute of Belgium in Uccle, Brussels. Models were first evaluated on a hourly and sub-hourly basis using measurements of global horizontal irradiance (GHI) as input. Second, the best performing ground-based decomposition models were used to extract the direct component of the global radiation retrieved from Meteosat Second Generation (MSG) images. Results were then compared to direct beam estimations provided by satellite-based diffuse fraction models and evaluated against direct solar radiation data measured at Uccle. Our analysis indicates that valuable DNI estimation can be derived from MSG images over Belgium regardless of the satellite retrieved GHI accuracy. Moreover, the DNI retrieval from MSG data can be implemented on an operational basis.

1. Introduction

Increasingly, developers are in need of direct beam solar irradiance data for site resource analysis, system design, and plant operation. Ideally, such information should be obtained from a dense network of stations where direct normal or horizontal global and diffuse radiations are routinely measured. However, due to equipment costs and maintenance, such measurements are scarce. In the absence of actual ground measurements, models have been developed to estimate the temporal and spatial variability of the solar resources. There are two approaches to model the direct beam radiation: models based on physical principles, and models for converting (or extracting) direct beam data from existing hemispherical data. Direct beam models based on physical principles apply cataloged absorption and scattering data, spectrally or as parameterized transmittance functions (for ozone, atmospheric gases, water vapor, and molecular or Rayleigh scattering), to the extraterrestrial direct beam spectral radiation. Decomposition models are based on empirical correlation between global horizontal irradiance (GHI) and diffuse horizontal irradiance or direct normal irradiance (DNI).

The present study focuses on the evaluation of decomposition models of various complexity with a view to using them on an operational basis to generate DNI estimation over Belgium at high spatial and temporal resolution. Although ground measurements are limited, satellite data can be used to calculate estimates of direct solar radiation where ground measurements do not exist. This possibility comes from the fact that back-scattered solar radiation from Earth-atmospheric system captured by a satellite can be statistically (e.g., Tarpley [1]; Cano et al. [2]) or physically (e.g., Gautier et al. [3]) related to the global irradiation at the Earth's surface, and direct component of the global radiation can be extracted from the global radiation by using diffuse fraction models. Moreover, satellite-derived datasets have the advantage of containing estimates of direct solar radiation with spatial uniformity for long-time periods to complement ground measurements.

There have been many efforts in the past to develop ground-based algorithms for the derivation of the diffuse fraction of solar

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irradiance on an hourly basis. This time step is widely used in most of the simulation processes. However, since 2004, Meteosat Second Generation (MSG, Schmetz et al. [4]) satellites operated by Eumetsat provide images of Africa and Europe every 15 min. It is therefore relevant to investigate the applicability of such models on sub-hourly time step. Towards this objective, 10 ground-based decompositions models were first evaluated on a hourly and sub-hourly basis against one year of in situ observations performed on the roof of the radiometric tower of the Royal Meteorological Institute of Belgium (RMI) in Uccle, Brussels. Second, the three best performing models together with a model well-suited for an operational use were used to extract the direct component of the global radiation retrieved from MSG images over Belgium. Results were then compared to direct beam estimations provided by two satellite-based diffuse fraction models and evaluated against the direct solar radiation data measured at Uccle.

The paper is organized as follows. A short summary of the selected ground- and satellite-based decomposition models is provided in Section 2. In situ measurements are briefly described in Section 3. Models performances are evaluated in Section 4. Final remarks and conclusions are provided in Section 5. Note that because atmospheric transmission models require detailed information of atmospheric conditions they were not considered in this study.

2. Selected decomposition models

Decomposition models are based on the correlation between the clearness index, k_t, defined as the ratio of the global horizontal irradiance to the irradiance available out of the atmosphere (i.e. the extraterrestrial irradiance multiplied by the sinus of the sun height) and the diffuse fraction (ratio of the diffuse-to-global irradiance), k_d, or the beam transmittance (ratio of the direct beam solar irradiance to the extraterrestrial solar irradiance) k_b. Several decomposition models ranging from very simple formulations (i.e., only considering k_t as predictor) to more elaborate expressions accounting for multiple predictors have been analyzed.

2.1. Ground-based decomposition models

2.1.1. Orgill and Hollands model (Ohm)

Based on Liu and Jordan [5] who introduced the notion that the ratio of diffuse to global radiation incident on a horizontal surface should be a well-behaved function of the global transmissivity of the atmosphere, Orgill and Hollands [6] proposed the first correlation between the hourly clearness index, k_t, and the corresponding diffuse fraction, k_d:

$$k_d = \begin{cases} 1.0 - 0.249\, k_t & k_t < 0.35 \\ 1.577 - 1.84\, k_t & 0.35 \le k_t \le 0.75 \\ 0.177 & k_t > 0.75 \end{cases} \tag{1}$$

Their model was based on global and diffuse irradiance values registered in Toronto (Canada, 42.8°N) in the years 1967–1971.

Once the diffuse fraction is obtained from the k_d-k_t correlation, the direct beam normal irradiance, I_{b_n}, is obtained by:

$$I_{b_n} = \frac{I_g(1 - k_d)}{\sin\alpha} \tag{2}$$

where I_g is the global horizontal solar irradiance and α, the solar elevation angle, respectively.

2.1.2. Erbs model (Erb)

Erbs et al. [7] adapted the Orgill and Hollands's correlation (Eq. (1)) to extend it to latitudes from 31° and 42° North based on 5 stations data. In each station, hourly values of direct and global irradiances on a horizontal surface were registered. Diffuse irradiance was obtained as the difference of these quantities. The proposed correlation combines a linear regression for $0 < k_t \le 0.22$, a fourth degree polynom for $0.22 < k_t \le 0.8$ and a constant value for $k_t > 0.8$:

$$k_d = \begin{cases} 1 - 0.09\, k_t & k_t \le 0.22 \\ 0.9511 - 0.1604\, k_t + 4.388\, k_t^2 - 16.638\, k_t^3 + 12.336\, k_t^4 & 0.22 < k_t \le 0.8 \\ 0.165 & k_t > 0.8 \end{cases} \tag{3}$$

2.1.3. Reindl models (Rd1 and Rd2)

Reindl et al. [8] estimated the diffuse fraction, k_d, using two different models developed with measurements of global and diffuse irradiance on a horizontal surface registered at locations in the USA and Europe (28–60°N). The first model (hereafter referred to as Rd1) estimates the diffuse fraction, k_d, using only the clearness index, k_t, as predictor:

$$k_d = \begin{cases} 1.020 - 0.248\, k_t & k_t \le 0.3 \\ 1.45 - 1.67\, k_t & 0.3 < k_t < 0.78 \\ 0.147 & k_t \ge 0.78 \end{cases} \tag{4}$$

The second correlation (hereafter referred to as Rd2 model), estimates the diffuse fraction, k_d, in terms of the clearness index, k_t, and the solar elevation angle, α:

$$k_d = \begin{cases} 1.020 - 0.254\, k_t + 0.0123 \sin\alpha & k_t \le 0.3 \\ 1.400 - 1.749\, k_t + 0.177 \sin\alpha & 0.3 < k_t < 0.78 \\ 0.486\, k_t - 0.182 \sin\alpha & k_t \ge 0.78 \end{cases} \tag{5}$$

2.1.4. Louche model (Lou)

Louche et al. [9] proposed a model that estimates direct irradiance values from direct transmittance values. Based on global and direct irradiance data measured at Ajaccio (Corsica, France, 44.9°N) between October 1983 and June 1985, they found the following correlation between the clearness index, k_t, and the beam transmittance, k_b:

$$k_b = -10.627\, k_t^5 + 15.307\, k_t^4 - 5.205\, k_t^3 + 0.994\, k_t^2 - 0.059\, k_t + 0.002 \tag{6}$$

2.1.5. Skartveit and Olseth model (Som)

Skartveit and Olseth [10] estimated the direct normal irradiance, I_{b_n}, from the global horizontal irradiance, I_g, and the solar elevation angle, α, for Bergen (Norway, 60.4°N) with the following equation based on hourly records of global and diffuse horizontal irradiance with mean solar elevation larger than 10° during 1965–1979:

$$I_{b_n} = \frac{I_g\,(1 - \Psi)}{\sin\alpha} \tag{7}$$