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The empirical models for estimating solar insolation in Serbia by using meteorological data on cloudiness

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A B S T R A C T

The paper presents empirical models for estimating solar insolation at a location in Serbia by using meteorological data on cloudiness. The models have been developed on the basis of the meteorological data on cloudiness and horizontal irradiation measurements at the locations of the city of Belgrade and the rural region of Bavanište in Serbia. In order to improve estimates of solar irradiation on clear days, the coefficients of annual variation of optical depth and the diffuse constant from the ASHRAE Clear Day model have been adjusted to the atmospheric conditions in Serbia. Furthermore, the ASHRAE Clear Day model has been enhanced by taking into account the daily optical depth and diffuse constant variations. The aim was to include real conditions on both clear and cloudy days throughout the year. Hence, a model that considers the influence of cloudiness on irradiation has been formulated. The developed models are simple and applicable in practice, as once they are established, only the basic meteorological data on cloudiness from the nearby measurement station are necessary for estimating the solar potential at a certain location.

1. Introduction

A photovoltaic (PV) system consists of photovoltaic modules and other components designed to transform the primary solar energy into electrical energy. Two most commonly encountered configurations of PV systems are grid-connected systems (feeding power directly into the utility grid) and stand-alone systems (supplying isolated consumers) [1].

PV systems are different from conventional electrical energy systems, since they are influenced by varying meteorological conditions. As a result, reliable solar insolation data are required at each site of interest for designing a PV system. It is essential that a location lacking an insolation database have accurate models for predicting insolation. The accuracy of these models affects the design, performance, and cost-effectiveness of solar systems [2]. By applying a variety of methods, these models take into account the influence of various atmospheric phenomena on solar irradiation [3]. The criteria for evaluating different models for estimating solar insolation should be simplicity, accuracy, and whether they can use the available meteorological data.

A wide group of models for estimating solar insolation is based on the assumption of a clear day [4–7]. A set of equations are used to predict the sun's position in the sky for a given location, as well as the insolation on the PV collector surface. However, owing to the great number of cloudy days per year, the results obtained by these models are not genuinely representative of the real conditions, although the models may apply thorough methods for solving the radiative transfer problem. One of the most commonly used clear day models is the one presented by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). The model is based on the empirical data collected by Threlkeld and Jordan [1,8].

Another group of models for estimating solar insolation use procedures for estimating the average insolation that can be expected on a collector surface, including methods which consider weather conditions at a particular site [9–14]. These models often use long-term measurements of solar irradiation on a horizontal surface [15–19]. A set of equations are then used to estimate the insolation on inclined collector surfaces. By using long-term solar irradiation measurements, solar researchers have developed many empirical models which determine the relation between solar radiation and various meteorological parameters [20]. The most

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Nomenclature

ASHRAE	the American Society of Heating, Refrigerating, and Air-Conditioning Engineers
PV	photovoltaic
SC	solar constant
n	the ordinal number of the day in the year
I_B	direct-beam radiation
A	apparent extraterrestrial flux
k	optical depth
m	air mass ratio
β	solar elevation
I_{BH}	the direct component of horizontal irradiation
I_{DH}	the diffuse component of horizontal irradiation
j	the ordinal number of the clear sky interval
k_{d}	the daily variation of optical depth
C_{d}	the daily variation of the diffuse constant
k'	the annual and daily variations of optical depth
C'	the annual and daily variations of the diffuse constant
I'_{BHCD}	the direct component of horizontal irradiation for a clear day
I'_{DHCD}	the diffuse component of horizontal irradiation for a clear day
p_{BH}	the relative value of the direct horizontal irradiation component
p_{DH}	the relative value of the diffuse horizontal irradiation component
cld	cloudiness

common meteorological parameters for predicting global solar radiation and its components are bright sunshine hours, cloud coverage, and temperature. Meteorological data on sunshine duration are easily obtainable from meteorological stations, so this is a frequent parameter for estimating solar radiation. The empirical models that use sunshine duration are based on the Angström correlation [21], i.e. on various modifications of the Angström–Prescott equation [22]. Models combining satellite images with surface measurements of bright sunshine hours have also been adopted for solar radiation estimation [23,24]. Also, there are very simple cloudy sky models that require only meteorological data on cloudiness [25–32]. Simple models for estimating global solar radiation on the basis of observations of various cloud layer amounts and cloud types have been developed in Refs. [25,26]. A simple empirical model for estimating global radiation based on mean daytime cloud coverage and maximum and minimum temperature has been tested in Ref. [27]. The analysis of cloud coverage and global radiation has shown a non-linear relationship. Also, a single formula relating direct beam energy over a day to observed cloud coverage has been used in Ref. [28], where a comparison with the global radiation measured at 12 stations has been performed. The Iranian meteorological stations' database has been used in Ref. [29] for establishing a simple relation between the sunshine duration records and cloud coverage. In Ref. [30], several very simple clear-sky and cloudy-sky global irradiation models were tested on the territory of Romania and under its climatic conditions. Next, the correlations between clearness index and fractional total cloud amount (point cloudiness) are derived in Ref. [31]. Finally, new models for computing hourly global solar irradiation from point cloudiness have been presented and tested in Ref. [32]. Although the listed cloudy models are simple, their performance is often comparable to that of the more complicated models [30].

This paper presents the empirical models for estimating solar insolation at a given location in Serbia. The parameters used in the presented models are based on the two-year measurements of horizontal solar irradiation for the city of Belgrade and the rural area of Bavanište in Serbia. The application of the established models at the selected locations requires only meteorological data on cloudiness available at the nearby hydrometeorological station [33,34]. By taking into account both the clear and cloudy sky conditions, the presented models enable a realistic estimation of solar insolation for the climatic region of Serbia.

The developed models may find their application in day ahead profile and in estimates of PV power plant production over a longer period of time. Furthermore, the significance of the developed models is seen in the fact that they can be applied to photovoltaic system design. These models provide more accurate data on the direct and diffuse solar irradiation components, which enable the optimization of PV panel tilt angles, and consequently optimize the production of PV power stations in the target region.

2. Data collection and analysis

The values used for developing the presented models were the ten-minute values of horizontal insolation and meteorological data on cloudiness measured at the locations of Bavanište and Belgrade during 2009 and 2013 respectively. The values of insolation components measured at the Belgrade location are somewhat lower compared to those measured at Bavanište under the same conditions of cloudiness. This discrepancy can be explained by the fact that Belgrade is a large city, evidently polluted by emissions from vehicles, industry, and heating plants, and the measurement set was positioned near a road with heavy traffic. In polluted areas, the insolated energy is somewhat lower owing to the presence of smog particles in the atmosphere. The measured energy may be additionally reduced by the layers of dirt deposited on the measuring equipment. In contrast, the measuring equipment at Bavanište was surrounded by vast plough lands where air pollution is minimal. Thus, the measured values were higher. Fig. 1 features a Solargis Map of Serbia with the locations of Belgrade (Beograd) and Bavanište indicated in red [35].

On the basis of the measured ten-minute values of horizontal irradiation obtained on all the clear days over the year, the direct and diffuse horizontal insolation components have been extracted by using Liu Jourdan's method. From the meteorological data recorded every day, three items of cloudiness data were extracted, those obtained at 7 a.m., 2 p.m., and 9 p.m. These items are expressed in tenths of the measured cloud coverage. Next, the cloudiness values for all ten-minute intervals in 2009 and 2013 were calculated by means of interpolation. Fig. 2 shows a portion of the annual diagram of cloudiness variation obtained for the region of Bavanište in 2009. It is considered that a clear interval is any interval involving cloudiness function lower than 2 tenths, Fig. 2. A verification of clear intervals was carried out based on the measured horizontal irradiation values, whereby clear intervals correspond to a smooth curve of irradiation variation showing the expected values according to the ASHRAE Clear Day model.

The direct and diffuse horizontal irradiation components on clear days have also been calculated by applying the ASHRAE Clear Day model.

The ASHRAE Clear Day model assumes that solar radiation on a horizontal surface is the sum of the direct and diffuse components