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Generation of spatially dispersed irradiance time-series based on real cloud patterns

Moein Jazayeri*, Kian Jazayeri, Sener Uysal

Electrical and Electronic Engineering Department, Eastern Mediterranean University, Famagusta, Via Mersin 10, Turkey

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ABSTRACT

Clouds, being complex components of the atmosphere, have significant effects on power generation by photovoltaic (PV) systems. For example, shadows caused by the cloud coverage over a geographically distributed PV power plant may cause significant fluctuations in power generation by leaving a number of PV panels unable to generate power and contribute to power generation by the plant at each time instant. Thus, investigation of the mentioned effects on PV power generation requires realistic spatial irradiance information. Such information should be evaluated based on the existing real cloud coverage and its light transmission characteristics. This also provides the opportunity to select appropriate coping strategies against the mentioned negative effects of partial shading on PV plant's power output. This paper presents a modeling approach which generates Spatially Dispersed Irradiance Profiles (SDIPs) for PV arrays based on existing cloud patterns derived from local sky images taken at the application sites. The model gets the direct, diffuse and global irradiance values incident on a horizontal surface, which are primarily obtained utilizing a solar irradiance model (the Morf (2013) model), along with local sky images captured at the application sites and cloud transmittance values, as input data and yields site-specific Spatially Dispersed Irradiance Profiles (SDIPs) incident on the surface of inclined PV panels within PV application areas, as a result of process of the inputs. Utilization of local sky images and cloud transmittance values for different cloud types creates the opportunity for precise analysis of interactions of sunlight with the existing cloud type and hence, obtaining unique and site-specific irradiance profiles according to the existing cloud type and distribution in the sky. The model firstly detects the cloudy and clear-sky parts in the sky image and then instantly utilizes the most appropriate ellipse on the cloud layer associated with each solar panel through which the beam irradiance is received by the panel. The model also considers the light transmission characteristics of different cloud types as the parameter affecting the beam irradiance. The diffuse and ground-reflected irradiance components are assumed to be spatially constant and thus identical for all solar panels. Cloud base heights, as provided in the International Cloud Atlas (1987), are also utilized to calculate the ground area covered by each sky image. Daily irradiance sequences for different observation points in a PV array are simulated under partly cloudy sky conditions using a set of sky images and utilized for validation purpose of the proposed algorithm. It is demonstrated that instantaneous irradiance values, as well as daily irradiance sequences, differ from point to point in a geographically distributed PV application site depending on the distribution of clouds in the sky. The mentioned variable characteristic of the irradiance sequences received at different observation points, as well as the model's capability to reflect the mentioned variabilities, is verified using irradiance data derived from satellite observations. The performance of the proposed model is validated using variability index (VI) metric as a measure of irradiance variability during a day. The modeled VI values are validated against the measured VI values for a reference point located at the center point of the generated irradiance profiles. Daily VI values calculated for both measured and simulated 1-min global horizontal irradiance (GHI) data are compared for a population of totally 117 days during April – August time period. The results of comparison show statistics of mean bias error (MBE) of 0.16, root mean square error (RMSE) of 2.394, correlation coefficient of 0.94 and mean absolute error (MAE) of 1.91. The validation results demonstrate capability and accuracy of the proposed model for estimation of irradiance values under cloudy sky conditions.

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* Corresponding author.
E-mail addresses: moein.jazayeri@cc.emu.edu.tr (M. Jazayeri), kian.jazayeri@cc.emu.edu.tr (K. Jazayeri), sener.uysal@emu.edu.tr (S. Uysal).

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Nomenclature

AM	Air mass
a,b	Ångström-Prescott regression coefficients
$cc(t)$	Cloud cover [Oktas, tenths]
$\overline{cc}$	Average cloud cover [Oktas, tenths]
$cc_e(t)$	Ellipse enclosed cloud cover (EECC) [Oktas, tenths]
$C_x(t)$	Coordinate of ellipse center on X axis
$C_y(t)$	Coordinate of ellipse center on Y axis
$\overline{D_o}$	Mean daily clear-sky diffuse fraction
$D_x(t)$	Major axis of ellipse
$D_y(t)$	Minor axis of ellipse
e	Eccentricity of ellipse
$G(t)$	Cloudy sky horizontal irradiance [W/m^2]
$G_b(t)$	Clear-sky horizontal beam irradiance [W/m^2]
$G_{b\beta}(t)$	Clear-sky inclined beam irradiance [W/m^2]
$G_{d\beta}(t)$	Clear-sky inclined diffuse irradiance [W/m^2]
$G_g(t)$	Array point cloudy sky horizontal irradiance [W/m^2]
$G_{g\beta}(t)$	Array point cloudy sky inclined irradiance [W/m^2]
$G_o(t)$	Clear-sky horizontal irradiance [W/m^2]
$G_{o\beta}(t)$	Clear-sky inclined irradiance [W/m^2]
$G_{r\beta}(t)$	Clear-sky ground reflected irradiance [W/m^2]
$G_{x,y}(t)$	Irradiance at point (x,y) [W/m^2]
$G_\beta(t)$	Cloudy sky inclined irradiance [W/m^2]
$G_0(t)$	Extraterrestrial solar irradiance [W/m^2]
ΔG	Irradiance increment [W/m^2]
h	Elevation above sea level
H	Daily horizontal global irradiation [J/m^2]
$\overline{H_o}$	Mean daily clear-sky horizontal global irradiation [J/m^2]
H_0	Daily irradiation outside the earth‘s atmosphere [J/m^2]
$\overline{H_b}$	Mean daily clear-sky horizontal beam irradiation [J/m^2]
$\overline{K_d}$	Mean daily clear-sky diffuse clearness index
LT	Local time
LST	Local solar time
m	Image size for cloud pattern
R_b	Ratio between beam irradiance on inclined and horizontal surface
R_{cc}	Range of cloud cover [Oktas, tenths]
R_{cce}	Range of EECC [Oktas, tenths]
R_d	Ratio between diffuse irradiance on inclined and horizontal surface
R_G	Range of array point irradiance values [W/m^2]
$SIF(t)$	Stochastic insolation function
$\overline{H_d}$	Mean daily clear-sky horizontal Diffuse irradiation [J/m^2]
k,l	PV array size
$\overline{K_o}$	Mean daily clear-sky clearness index
$\overline{K_b}$	Mean daily clear-sky beam clearness index
SS	Sunset
φ	Latitude
x',y'	Cloud transmittance coefficient
α	Solar azimuth angle [degrees]
β	PV module tilt angle [degrees]
γ_s	Solar altitude angle [degrees]
δ	Solar declination angle[degrees]
θ_s	Solar incidence angle [degrees]
θ_z	Solar zenith angle [degrees]
μ_G	Mean of array irradiance values
$G_d(t)$	Clear-sky horizontal diffuse solar irradiance [W/m^2]
ρ	Ground reflectivity
$\overline{\tau}$	Cloud Transmission factor
τ_c	Cloud transmittance
τ	Time interval between irradiance measurements
ω	Hour angle
θ_p	Pixel zenith angle [degrees]
α_p	Pixel azimuth angle [degrees]

1. Introduction

High dependency of solar energy applications on the incident solar irradiance causes a vital need to obtain precise knowledge regarding solar irradiance levels received by each individual PV module within the application areas to create the opportunity for appropriate design and management of PV systems. Large-scale centralized PV power plants or PV plants distributed on a wide geographical area can be considered as examples of such applications. Power generation in such plants is also highly dependent on the non-identical irradiance levels incident on the surface of PV panels within the PV power plant, that are caused by cloud passages. Dependence of power generation in PV power plants on the received non-identical irradiance values caused by the real-time passing clouds is one of the main reasons for the need to the site-specific irradiance data. Unavailability of instantaneous data or limitations associated with the measurement stations have led to development of solar radiation estimation and/or simulation models. Numerous models have successfully been developed for clear-sky solar irradiance where the main emphasis is put on modeling of the beam component of the irradiance due to its importance for solar energy systems.

Clouds, at the same time, as some complex elements of the climate, have significant impacts on the incident irradiance. Thus, a good model, from PV system's point of view, should necessarily account for cloud properties to include the effects of interactions of the existing clouds with the incoming solar irradiance. The output of such a model being capable of estimation of solar irradiance under cloudy sky conditions can be considered as a reliable input for the desired PV applications.

The goal of this paper is to develop a model to generate spatially dispersed irradiance profiles incident on PV power plants extended in a wide geographical area or distributed PV power plants, taking into account the existing cloud coverage at the intended application sites. In this way, precise information on the amount of solar irradiance received by each individual solar panel within the PV power plant can be obtained at each desired instant of time. Consequently, estimation of power production and taking necessary actions to cope with negative effects caused by non-identical irradiance levels received by different solar panels in a PV plant is facilitated. As it is discussed in the further parts of the paper, the developed model mainly utilizes clear-sky global irradiance as well as the direct and diffuse irradiance components and accounts for light transmission characteristics of the existing cloud coverage to generate the mentioned irradiance profiles.

As mentioned previously, since the beam or direct irradiance component is more important from solar energy employing system design point of view, emphasis is mostly put on estimation of the mentioned irradiance component. Models introduced in the literature for estimation of direct or beam component of solar irradiance are mainly categorized under two groups as (Wong and Chow, 2001);

(1) Parametric Models
(2) Decomposition Models

(ASHRAE, 1999; Iqbal, 1983; Davies and McKay, 1989; Gueymard, 1993) are some of widely utilized parametric models while (Liu and Jordan, 1960; Erbs et al., 1982; Reindl et al., 1990a; Skartveit and Olseth, 1987; Louche et al., 1991) are provided as examples of decomposition models in the literature. Parametric models require detailed information regarding the atmospheric conditions such as cloud type, cloud coverage and distribution in the sky, sunshine duration, etc., while decomposition models only utilize global irradiance to estimate direct and diffuse irradiance components. The ASHRAE model is widely utilized due to its simplicity over the other models while a