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Enhanced values of global irradiance due to the presence of clouds in Eastern Mediterranean

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ABSTRACT

During cloudy conditions, the presence of clouds in the sky in relation to the sun's position may result in obscuring the sun's direct irradiance to a Photovoltaic Park, and thus in a reduction in the solar irradiance directly, and in energy production indirectly. Nevertheless, during partially cloudy conditions, diffuse irradiance at the PV park may be enhanced due to the reflection of solar irradiance from the base of the clouds and from the scattering of direct irradiance due to cloud particles. Such periods of enhanced solar irradiance may last from several seconds to some minutes depending on the cloud motion. This paper presents measurements of enhanced global irradiance from data obtained in Cyprus (latitude 34.7° N, longitude 32.6° E), during the spring and summer of 2010. On seven occasions in five different days of May and June, the measured value of global irradiance exceeded 1500 Wm^{-2} that corresponds to 150% of the theoretical value computed by Bird and Hulstrom clear-sky computational model for those specific occasions. Moreover, it is noteworthy that in more than 20 days of April, May and June, the 1 min and 10-min average global irradiance exceeded 1200 Wm^{-2} (enhanced by 125% compared to the theoretical ensembled averaged value for those specific occasions) showing a long lasting period of this effect. These long periods of high irradiance values, along with the temperature drop due to the presence of clouds (the ambient temperature in the summer near noon is in the range of 30–40 °C while the measured temperature was in the range of 15–20 °C) might boost the performance of photovoltaic modules and cause irreparable damage to photovoltaic inverters.

1. Introduction

Solar Irradiance is the feedstock for various Renewable Energy Source (RES) technologies, either by exploiting global solar irradiance such as Photovoltaics (PV), commercial solar updraft towers and residential/commercial solar heating and cooling systems or by exploiting only the Direct Normal Irradiance (DNI), such as solar troughs, solar tower plants and solar dish technologies.

DNI is the amount of solar radiation that comes directly from the sun and is incident on a surface that is always perpendicular to the direction of the sun rays. Global Irradiance is the total amount of the incident irradiance on a surface and is the sum of the DNI and the diffuse irradiance. Diffuse irradiance is the part of irradiance that is scattered or reflected by atmospheric components of the sky or by the surface of the earth (in the case of tilted surface only). Global irradiance is usually measured on a horizontal surface, (Global Horizontal Irradiance, GHI) or on an inclined surface concerning specific applications. Global Irradiance on an inclined surface can be estimated from other meteorological data using mathematical formulas [1–3].

Various models have been proposed for the estimation of GHI either with no exogenous inputs using only the extraterrestrial radiation (solar constant), solar declination, sunshine duration, geographical location and date/time, or with additional exogenous parameters such as air temperature, earth surface albedo, relative humidity, cloudiness, precipitation, evaporation, atmospheric composition, aerosol optical depth and soil temperature [4–6]. From these parameters, the most profound parameter for solar irradiance variations is cloudiness, because although it can be predicted, the spatial and temporal resolution of the predictions is very low, resulting in an uncertainty in solar energy generation prediction, especially for Solar Power Systems without energy storage, such as PV parks [7].

The solar constant is the intensity of solar irradiance that is incident to the earth's atmosphere. The value of solar constant is 1367 Wm^{-2} ± 3.3% [8]. During the transition of solar radiation through the atmosphere of the earth, the intensity of irradiance is attenuated due to absorption and scattering by atmospheric

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particles such as clouds and aerosols. Thus, during cloudy conditions, the presence of clouds results in the attenuation of DNI that results in a corresponding decrease in the intensity of global irradiance. Nevertheless, occasionally, the combination of the above different parameters leads to a perfect storm which may result in the enhancement of global irradiance, thus achieving irradiance values even higher than the solar constant [9].

The enhancement of solar irradiance occurs under specific partial cloudy conditions. Piacentini et al. [9] proposed that the following conditions should coexist:

1. Presence of Cumulus clouds around the sun disk with the sun unobstructed, i.e. the clouds should not be present between the sun disk and the measurement point on the ground. The direct sun's radiation should be reflected by the edges of the clouds.
2. The minimum cloud coverage should be not less than 50% and the maximum not more than 90%, thus, allowing patches of clear-sky between clouds.
3. Clouds should be very thick in order to scatter solar radiation and increase the intensity of diffuse irradiance.

Additionally to these, Yordanov et al. [8] proposed that irradiance enhancement may be also attributed to strong forward Mie scattering of light inside the clouds within a narrow angle around the solar disk. As they have shown in their research, during Mie scattering, 51% of all scattered photons concentrated within 5° in the forward directions, thus contributing to the enhancement of irradiance. Thus, in some cases, when the sun is obscured by clouds, strong light is emitted within the clouds caused by Mie scattering. A similar statement was presented earlier by Rouse [10] proposing that if the cloud top albedo is small and the cloud base and the terrestrial high albedos, most of the radiation is to be transmitted through the cloud and strongly enhanced by multiple reflections between the surface of the earth and the cloud base.

Although the weather conditions that cause irradiance enhancement are not rare, exceptionally high values of irradiance occurrences are not often mentioned in the bibliography. This is mainly due to the long response time of the pyranometers used, thereby ignoring instantaneous fluctuations of irradiance or because the recorded data include the average value of irradiance only and not the maximum one [11]. The pyranometers used in various bibliographic references have a response time of 18 s which is very long compared to modern pyranometers with response times less than 5 s [8,12], as those used for the measurements presented in the following sections.

Nevertheless, short term enhancements of GHI may exceed 1500 Wm^{-2}, whereas peaks reaching 2000 Wm^{-2} may be observed in mountainous regions near the equator. Piacentini et al. (2003) [13] reported a maximum value of GHI of 1528 Wm^{-2} at an altitude of 3900 m in Argentina and, in a subsequent study at sea level near the equator, a maximum intensity of 1477 Wm^{-2} was recorded [9]. Yordanov et al. [8] measured the enhancement of global irradiance on a tilted surface in Norway. The measured global irradiance reached a maximum value of 1528 Wm^{-2}, although they reported incidents of maximum measured GHI of 1800 Wm^{-2} in Kenya near the equator. Suehrcke and McCormick [11] reported that they observed instantaneous values of GHI greater than the solar constant in Western Australia. Emck and Richter [12] presented a study regarding 4 year measurements of GHI in the southern Ecuadorian Andes Mountains near the equator, at an altitude of over 1900 m, where they observed multiple occurrences of GHI exceeding 1700 Wm^{-2}, while the maximum recorder value reached 1832 Wm^{-2}. Cede et al. [14] recorded enhanced values of total irradiance at four sites in Argentina. At all four sites, the maximum recorded values of total irradiance were enhanced by 135% with respect to the very clear-sky situation; the maximum measurements of 15-min average and 60 min average were 123% and 120% respectively. Luoma et al. [15] used a very fast (response time $< 10\ \mu s$) pyranometer to determine the energy loss from PV systems due to irradiance enhancement. Their measurements showed measured GHI greater than 1300 Wm^{-2} that was equivalent to 1500 Wm^{-2} for global irradiance on a tilted surface. Gu et al. [16] stated that they recorded enhanced values of irradiance almost every day for a two month period in Brazil, recording maximum values of GHI greater than 1400 Wm^{-2}. Schade et al. [17] observed irradiance enhancement of more than 500 Wm^{-2} compared to clear-sky values on the North Sea island of Sylt, Germany. Hansen et al. [18] presented recorded values of GHI up to 1500 Wm^{-2} in Albuquerque in New Mexico at an altitude of 1600 m.

The aim of this paper is to measure GHI in Cyprus, compare the measurements to the theoretical values of GHI for clear-sky conditions, calculate the percentage of measurements higher than the modeled ones, and evaluate the reason for these events and when they occur (i.e. middays, summer period etc.).

In Section 2, the equipment used for the measurements and the irradiance model used to calculate the clear-sky irradiance are described. In Section 3, a statistical analysis of the measurements is presented, and the recorded data are compared to the computed values of irradiance. The discussion of the results, with relevance to their effect on PVs, is presented in Section 4 and the conclusions in Section 5.

2. Equipment and computational model

The equipment used for the measurements is a remote meteorological station based on Geónica's Meteodata 3000 data transmission system positioned in Paphos, Cyprus (34.675N, 33.045E). The station consists of various measuring sensors, such as a pyrheliometer for measuring DNI, pyranometers for measuring GHI and diffuse irradiance, anemometer and wind vane and air temperature and humidity sensors. The pyrheliometer for measuring DNI and the pyranometer for measuring diffuse irradiance are positioned on a solar tracker.

The pyranometers (model MS-802) are ISO 9060 Secondary Standard with response time 5 s and the pyrheliometer (model DN01) is ISO 9060 first class, with response time 18 s. The temperature sensor's range and accuracy are -30 °C to $+70$ °C and ± 0.1 °C, respectively. The solar tracker (Model SunTracker-3000) is a two axis tracker (360° Azimuth, 90° elevation) with $\pm 0.1°$ accuracy. The measurements from the sensors were recorded and stored on the datalogger and transferred to a computer server and then to a workstation for further processing. The measurements were taken from November 2009 to November 2010.

In order to be able to evaluate the measurements from the meteorological station, the theoretical values of the irradiance for any given instance were first computed and then compared to the measurements. The computational model used for the estimation of solar irradiance is that developed by Bird and Hulstrom in 1981 [19]. The model computes hourly values of direct normal, direct horizontal, global and diffuse irradiance for every day of the year. The parameters of the model were modified regarding the geographical location of the meteorological station (latitude 34.7° N, longitude 32.6° E, altitude 360 m) and the atmospheric parameters of the site. Great attention was paid was given to the parameter regarding the albedo of the specific site, quantified to 0.4 since the surrounding surface is semi-desert with high reflectivity [20,21]. Since the Bird's model computes the average hourly values of the irradiance, the calculations were interpolated to the intermediate 10-min and 1-min values using cubic interpolation. Since the All the calculations were computed by an algorithm developed