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Estimation of sunshine duration from the global irradiance measured by a photovoltaic silicon solar cell

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ABSTRACT

Sunshine duration can be estimated using photovoltaic solar cells instead of conventional pyranometers or pyrheliometers, which are more expensive and therefore not suitable for low cost measurement applications in developing regions. A one-year meteorological dataset from Nicosia (Cyprus) including direct irradiance, global irradiance from a pyranometer and global irradiance from a reference PV cell was used to calculate sunshine duration following the WMO pyrheliometric method and three pyranometric methods by WMO Slob and Monna, Hinssen–Knap and Olivieri. Pyranometric algorithms were adapted to the tilted pyranometer and reference solar cell. Main results indicate that all the pyranometric algorithms underestimated sunshine duration over the span of a year in Cyprus in comparison with the reference pyrheliometric method; and that results between the pyranometer and the solar cell were comparable. The PV silicon solar cell is capable of measuring sunshine duration on a daily basis with an uncertainty similar to the obtained with a pyranometer when using the Olivieri algorithm.

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1. Introduction

The World Meteorological Organisation (WMO) [1] defines sunshine duration (*SD*) as the number of hours for which the direct solar irradiance is above 120 W/m^2. This type of measurement is often used in low cost renewable energy applications, for example in solar water purification processes such as solar disinfection (SODIS) [2–5]. A common approach to SODIS in developing countries uses plastic bottles exposed to the sun to purify water. It requires that for a sunny day, 6 h of sunshine is needed to treat the water and make it safe to drink. In cloudy conditions, the time required for the water purification increases to 2–3 days. Therefore,

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a low-cost sensor capable of estimating the sunshine hours would be suitable for SODIS water treatment and would improve its effectiveness and spread in developing areas [6–9].

The aim of this study is *to determine if a photovoltaic (PV) silicon solar cell can be used to measure sunshine duration*, and therefore serve as a sensor for low-cost solar technology applications such as solar water purification. To evaluate the suitability of this approach, the different algorithms proposed by the WMO for *SD* calculation from direct irradiance, global irradiance and diffuse irradiance will be compared using a pyrheliometer, pyranometer and silicon cell.

The algorithms that use only global irradiance from a pyranometer will be applied to the case of global irradiance data that come from a PV silicon solar reference cell [10]. A comparison will be made between the sunshine duration calculated by the PV cell with the *SD* values obtained from data from the pyranometer and pyrheliometer. The correlation between the data from the cell and the data from the pyranometer, as well as possible limitations and possible correction factors, will be studied in order to conclude whether the cell is suitable or not for the measurement of sunshine duration.

2. Sunshine duration measurement

There are different methods to determine the sunshine duration according to the WMO [1], including direct measurement with the Campbell–Stokes recorder, the pyrheliometric method using direct irradiance from a pyrheliometer, or pyranometric algorithms using the global irradiance from a pyranometer. There are also additional pyranometric methods not adopted yet by the WMO but that are well-reviewed in the literature aiming to improve the pyranometric algorithm used by the WMO [11–13].

2.1. Campbell–Stokes sunshine recorder

This instrument was introduced in 1880, and is composed of a glass sphere that concentrates the solar radiation beam onto a graduated paper card that burns according to a sunshine intensity threshold. The sunshine duration is read from the total burn length [14,15]. The WMO considers that it does not provide accurate data as the burns are subjected to errors caused by possible mounting adjustments problems and to the fact that the burns depend heavily on the card temperature and humidity [1,16].

2.2. Pyrheliometric method

The sunshine duration definition given by the WMO as '*the number of hours for which the direct solar irradiance is above 120 W/m^2*' requires a more accurate method than the Campbell–Stokes recorder. In this regard, direct solar irradiance is measured by a pyrheliometer held normal to the sun by a sun tracker and monitored automatically [17]. A pyrheliometer measures only the direct and circumsolar irradiance by using a thermopile with a broadband spectral response (typically from below 200 nm to 4000 nm) and with a narrow aperture. It requires continuous sun tracking. The sunshine duration is then obtained by integrating the time over the day length during which the direct solar irradiance exceeded the threshold of 120 W/m^2. In summary, the data required and the sunshine duration calculation using the pyrheliometric method are as follows:

- *Data*: Direct solar irradiance from a pyrheliometer with a resolution of 1 min.
- *Sunshine duration*: Period composed by the sub-periods in which the direct solar irradiance is above 120 W/m^2. The sub-period is 1 min.

2.3. Pyranometric methods

Other methods used by the WMO are based on the measurement of global irradiation using a pyranometer. A pyranometer consists of a thermopile with a broadband spectral response; similar to a pyrheliometer, but in this case the aperture is not narrowed but widened using a semispherical glass dome. If a shading ring or a shading ball is used to block the direct radiation reaching the pyranometer the diffuse radiation can be obtained. The shading ball requires full two-axis sun tracking, whereas the shading ring requires weekly elevation adjustment.

The relationship between direct, global and diffuse solar radiation is

$$I\cos\theta = G - D \tag{1}$$

where I is the direct solar radiation normal to the plane of measurement, $I\cos\theta$ is the horizontal component of the direct solar radiation, θ is the solar zenith angle, G is the global solar horizontal radiation, and D is the diffuse solar horizontal radiation.

If there are ***two pyranometers*** available, one for global solar radiation and one for diffuse solar radiation then the WMO method can be used to calculate the direct solar radiation component by using the relationship given in Eq. (1). Sunshine duration can then be calculated by filtering for periods where the threshold of 120 W/m^2 is exceeded. Therefore, this method uses

- *Data*: Global solar irradiance from a pyranometer and Diffuse solar irradiance from a pyranometer with shading ring or shading ball and tracker, with 1-min resolution.
- *Sunshine duration*: Period composed by the 1-min sub-periods in which the direct solar irradiance, calculated as $I = (G-D)/\cos\theta$, is above 120 W/m^2.

However, if there is only ***one pyranometer*** available, measuring global horizontal solar radiation, then the sunshine duration calculation is not so straightforward. Several algorithms have been proposed by different authors [11–13] that use the global horizontal and other common parameters, such as the latitude, longitude, cloud cover, turbidity, temperature, etc. Some of these algorithms are described in the next sub-section. Of these, the WMO currently uses the Slob and Monna algorithm. Slob and Monna developed this algorithm in 1991 [18]. It uses the mean, minimum and maximum of global solar radiation in a 10-minute interval. It is based on an estimation of the direct (Eq. (2)) and diffuse (Eq. (3)) components for cloudless conditions, which depends on the Linke turbidity factor T_L [19] (related to the trace gases and aerosols in the atmosphere), the solar constant ($I_0 = 1367\ W/m^2$) and the cosine of the solar zenith angle ($\mu_0 = \cos\theta$). These estimations are based on a three year dataset in the Netherlands (1986–1989) and are as follows:

$$I = I_0 \exp(-T_L/(0.9 + 9.4\mu_0)) \tag{2}$$

where I is the parameterised estimation of direct solar irradiance for cloudless conditions, I_0 is the solar constant, T_L is the turbidity factor and μ_0 is the cosine of the solar zenith angle.

$$D/G_0 = \begin{cases} 0.2 + \mu_0/3 & \text{for } 0.1 \le \mu_0 \le 0.3 \\ 0.3 & \text{for } \mu_0 \ge 0.3 \end{cases} \tag{3}$$

where D is the parameterised estimation of diffuse solar irradiance for cloudless conditions and G_0 is the horizontal radiation in the atmosphere ($G_0 = I_0\mu_0$).

The algorithm compares the measured global solar irradiance G with the lower limit for cloudless conditions, which is $I\mu_0 + D$. This comparison is conducted with all the values normalised by G_0. Fractional values of sunshine f are then calculated for 10-min intervals (0 – no sunshine at all, 1 – only sunshine, between 0 and